Perspectives on Power Electronics and Grid Solutions for Offshore Wind farms

Elforsk rapport 10:96

Hans-Peter Nee and Lennart Ängquist

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Vindforsk Energimyndigheten ELFORSK

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Preface

Lately several projects have been launched, predominantly in northern Europe, with offshore wind farms that are connected to separate connection points in the national onshore electrical AC system.

In some countries local offshore networks collecting power from several wind farms have been proposed (DK, UK) and implemented (NO). Some organisations, e.g. SSE Renewables (Scottish and Southern Energy plc, former Airtricity), have presented visions about a future offshore network with connections to several European nations.

The purpose of this report is to gather, asses and document information about the technical solutions that are available to meet this kind of proposals. It focuses on systems that involve power electronics as an essential component in the power transmission system, i.e. systems based on high voltage direct current (HVDC) technology.

The work has been carried out by professors Hans-Peter Nee and Lennart Ängquist at Royal Institute of Technology (KTH) in Stockholm as a project within the Swedish wind energy research programme "Vindforsk III". The report is the final report for project V-340.

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Comments on the work and the final report have been given by a reference group with the following members: Kjell Gustafsson from Statkraft, Elisabet Norgren from Svenska Kraftnät and Urban Axelsson from Vattenfall Research and Development.

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Sammanfattning

Målet med denna studie är att utvärdera effektelektroniska teknologier för havsbaserade transmissionssystem för sammanbindning av havsbaserade vindkraftsparker och det högspända växelspänningsnätet på land. Särskild uppmärksamhet har fästs vid utvärdering av teknologier för högspända likströmstransmissionsnät, eftersom dessa förväntas ha särskilt goda egenskaper när avstånden till en stark inkopplingspunkt till nätet på land är stora.

De europeiska planerna för massiva investeringar i havsbaserad vindkraft innebär exceptionellt hög belastning av det existerande högspända växelspänningsnätet. Idéer att skapa ett havsbaserat SuperNät har framförts av flera sammanslutningar, men kostnaderna för ett sådant nät är överväldigande och de tekniska utmaningarna är omfattande. Utöver transmissionssystemet som sådant har även närliggande ämnen såsom uppsamlingsnät diskuterats kortfattat.

För att undersöka det som nämnts ovan har en noggrann litteraturstudie genomförts. Artiklar från vetenskapliga tidskrifter och konferenser samt information från internet har sammanställts. Vetenskapliga konferenser har besökts och ett antal intervjuer (av vilka tre har rapporterats explicit) har genomförts. Resultatet av dessa studier har satts i relation till forskningen som utförts av de undertecknade själva. På grundval av dessa studier har följande slutsatser dragits.

I dagsläget utgör havsbaserad vindkraft endast ett fåtal procent av all installerad vindkraft. De havsbaserade projekten ärver därför i avsevärd grad teknologi från landbaserad vindkraft. Vindkraftsparker nära kusten kommer därför att använda sig av växelströmskablar för transmission till fastlandet om avståndet är tillräckligt kort. När vinkraftparkerna flyttar längre ut i havet måste växelströmskablarna bytas ut. Sedan länge har högspänd likström betraktats som det naturliga, och kanske enda, möjliga alternativet. Flera metoder för implementering av sådana högspända likströmsöverföringar har framförts av tillverkarna i det förgångna, men på sistone tycks åsikterna från de olika tillverkarna konvergera till en gemensam grundläggande princip. Denna bygger på spänningsstyva omvandlare med en ny multinivåteknik med kaskadkopplade bryggor. Tekniken har rönt stort intresse både inom industri och akademi. Anledningen till detta är att utspänningar med exceptionellt hög kvalitet förenas med omvandlarverkningsgrader som med råge överstiger 99%. Åtminstone två tillverkare har visat att de är kapabla att offerera denna teknik, vilket är ett bevis på potentialen för tekniken. Det är mycket sannolikt att de planerade stora havsbaserade projekten kommer att använda sig av denna teknik. År 2013 ska de två första samlingsnoderna (eng. hubs) vara i drift. Dessa samlingsnoder kan komma att bli de första noderna i ett havsbaserat högspänt likströms-supernät som bygger på omvandlare med kaskadkopplade bryggor.

Summary

The purpose of this study is to evaluate power electronic technologies for offshore transmission systems connecting offshore wind farms with the onshore high-voltage ac grid. Special emphasis has been put on evaluating suggested technologies for high-voltage DC transmission systems, which are anticipated to perform particularly well when the distance between the offshore wind farms and the strong connection points in the onshore network increases. Implementation of the European plans of massive investments in offshore wind power generation would impose exceptionally high stress on the existing high-voltage AC grid. Ideas to create an offshore SuperGrid have been suggested by several associations, but the costs for such a grid are overwhelming and the technical challenges are substantial. Apart from the transmission system as such, related topics such as collection grids, are also briefly discussed.

In order to investigate the items mentioned above, a thorough literature study has been performed. Scientific journals and conferences as well as information on the web have been compiled. Scientific conferences have been visited, and a number of interviews (of which three have been reported explicitly) have been performed. The outcome of these studies has been put in relation to the research performed by the authors. Based on the findings of the studies the following main conclusions could be drawn.

Presently offshore wind power only constitutes a few percent of the total number of wind power installations. Offshore projects therefore to a large degree inherit the onshore wind power technology. Accordingly wind farms located close to the shore will utilize AC cables to transfer the power to the mainland if the transmission distance is sufficiently short. When the offshore wind farms move further out in the sea, the AC cable power transmission system must be replaced. Since long time High-Voltage Direct Current (HVDC) transmission has been looked upon as the natural, and perhaps only, viable alternative. Several approaches, backed by different manufacturers, to implement such HVDC systems have existed in the past, but it appears to the authors that lately the opinions of the different manufacturers have converged towards a common fundamental principle. The approach is based on voltage source converters using a new multilevel technology with cascaded bridges. It has gained a great interest from both industry and academia. The reason for the great attention is that output voltage waveforms of exceptionally high quality can be combined with converter efficiencies well above 99%. At least two manufacturers have shown that they are capable of offering this technology, which is an evidence of the potential for the technology. It is very likely that the great offshore projects that are currently planned will make use of this technology. In 2013 the two first hubs for offshore wind power generation should be in operation. These hubs could be the first nodes of an offshore high-voltage DC SuperGrid based on multilevel converters with cascaded bridges.

Innehåll

1 Introduction

Substantial investments in wind power generation have taken place in the last years. During 2009 more than 10 GW of new capacity was added in EU and at the end of that year wind power will, in a normal wind year, produce 4.8% of EU's electricity [web_ewea_factsheets]. In the European Wind Initiative the target, proposed to the European Commission, is that 20% of Europe's energy comes from renewable energy sources 2020, 33% 2030 and 50% 2050 [web_ewea_ewi].

The high power has made it obvious that many wind turbines must be gathered into farms with rating of several hundred MW, which are then collectively connected to the existing electrical transmission network rather than to make separate connection of each turbine to the distribution network.

The absolute majority of wind farms are sited on land, but some are located offshore. In 2009 this share constituted 2.8% (2.4 GW) of Europe's total wind power [web_ewea_factsheets]. It is foreseen that the relative contribution of wind power coming from offshore will increase to 17% (40 GW) in 2020 and to 38% (150 GW) in 2030 [web_ewea_ewi].

Until recently all offshore wind farms have been placed close to the coast with transmission distances to the main land that are within reach for cable transmission using high voltage AC cables. However, when the wind farms are located further away from the coast, other power transmission systems must be considered. Systems based on high voltage direct current transmission (HVDC) are obvious candidates.

The cost structure of HVDC transmission in general shows a high initial cost and lower marginal cost per MW. Therefore it is natural to build a high capacity transmission link to an offshore hub, so that many wind farms can be connected and benefit from a common transmission link to the onshore network.

Once such hubs exist it appears reasonable to establish interconnections between the hubs in order to create a meshed DC network that can transfer large amounts of renewable electrical power over long distances. Simultaneously it is hoped that this would increase the utilization of the network investments. Many groups and organisations have studied and proposed establishment of such interconnected DC systems.

The purpose of this report is to collect, asses and document information about the technical solutions that are available to meet this kind of proposals. It becomes obvious that important functionality has not been implemented yet, but that development is successively approaching the state that makes DC grids realizable. It is felt that looking at the systems presently being installed may give a good indication of what will come.

The focus in this report is on power electronics used in HVDC transmission systems. It appears that a major step forward within this area has been taken by the development of multilevel voltage source converter technology.

2 Cables

It might appear unexpected that the report dealing with power electronics starts with a chapter about cables. However, the truth is that the cable development plays a very important role for the development of HVDC converters and vice versa.

2.1 AC cables

High voltage cables for 50 or 60 Hz transmission are available from several manufacturers. Different versions for installation on land or in submarine applications exist. Figure 2.1 shows cables using different insulation technology, mass-impregnated and cross-linked polyethylene (XLPE) respectively. Cables using XLPE insulation systems are available up to 420 kV for land cables and 245 kV for submarine cables.

Figure 2.1: High-voltage cables; mass-impregnated (left), XLPE-insulated (right)

(Source: Prysmian)

Due to the short distance between the conductor and the shield at ground potential cables exhibit a much higher shunt capacitance, in the order of 100-200 nF/km, as compared to that in overhead lines, 9-13 nF/km. The shunt capacitance in the cable is determined by the formula

$$C = \frac{\varepsilon_r}{18 \log\left(\frac{r_o}{r_i}\right)} \quad [\mu F / km]$$

where ε_r is the relative permittivity of the insulating material ($\varepsilon_r = 2.5$ for XLPE), r_i is the radius of the conductor screen and r_o the outer radius of the insulation. The very slow variation of the logarithmic function indicates that it is not possible to reduce the capacitance of the cable significantly simply by changing the dimensions in the existing concept.

Accordingly a large charging current flows through the cable terminals as soon as the cable is energized. The current is proportional to the length of the cable and even at moderate lengths, in the range of 50 – 150 km, the charging current magnitude approaches the cable's rated current. In theory several line segments can be connected in series, with compensating shunt reactors connected between the segments, in order to bridge longer transmission distances. However, for submarine transmission such compensators must be located offshore on platforms or on sea bottom, making this concept less attractive.

In [web_transmed_solar] the maximum power transfer on AC cables is discussed. It is claimed that the transfer capability only increases up to a certain voltage level due to dielectric properties. This level for a 1600 mm^2 copper cable is 500 kV for a mass-impregnated and 1200 kV for a XLPE-insulated cable. The maximum power transfer for a 2500 mm2 is said to be 1000 MW for the mass-impregnated cable and 1450 MW for the XLPE-insulated cable at 500 kV.

2.2 DC cables

Submarine cables for DC transmission have been manufactured since the first HVDC was launched in the 1950'ies. The cables used for classical HVDC transmission systems, called "mass-impregnated" cables, utilize an insulation system based on impregnated paper. The cables have a lead shield which forms an impervious layer that prevents water from entering into the insulation system. Such cables with voltage ratings up to 600 kV and current rating up to 1600 A, are available from several manufacturers. A lot of experience has been gained about this type of cables from a large number of installations all over the world. A characteristic of the classical HVDC technology is that the polarity becomes inverted when the power flow reverses. The mass-impregnated cable can handle this condition in a satisfactory way.

Extruded cross-linked polymeric insulation forms the insulation in another type of cables called "XLPE" cables. They are generally lighter and easier to handle than their mass-impregnated counterparts and they allow a higher temperature. In submarine applications the cable is provided with a lead shield and steel armouring. As the insulation material does not absorb water the lead shield can be omitted in land installations. The XLPE cables do not comply with HVDC systems requiring sudden voltage reversal like the classical HVDC systems. This is due to the risk of space charges that can arise with extruded insulation and which may create excessive dielectric stress at such events. However, new HVDC systems based on VSC technology do not need voltage reversal capability and accordingly XLPE cables fit very well in VSC converter based HVDC systems.

XLPE cables have been used for VSC-based HVDC systems in applications with voltages up to ±150 kV. The rated voltage in a HVDC project, presently under commissioning, is ±200 kV. Systems rated for ±300 kV and ±320 kV have been ordered.

2.3 Selection of cables for HVDC transmission systems

Most, but not all, cable manufacturers claim that the choice of cable technology for HVDC transmission in offshore applications depends on whether polarity reversal withstand capability is required or not. If required extruded cables are disqualified otherwise both types can be used.

For sub-marine applications the choice between XLPE and mass-impregnated cables is free. However, the latter are probably slightly more expensive due to a more complex design.

If a substantial portion of the transmission is on land, XLPE cables will be preferred because they are lighter and cheaper and easier to install because the lead shield is not needed.

The allowed current rating depends on the maximum steady state temperature. The main parameters determining the loading is the thermal resistivity and the temperature in the ambient sea water. The temperature drop across the insulation only causes a minor part of the temperature rise. Therefore the laying distance between cables has a substantial impact on the permitted loading.

Experience shows that it is practical to limit the cable ampacity to 1600 A or less. This corresponds to a cable diameter of around 1 dm. If more power is needed it is preferred to increase the voltage or to connect parallel cables. The latter alternative also can contribute to reliability by offering possible redundancy.

In any upcoming project a suitable voltage level is studied based on the required power transfer level. The cost function normally is a flat function of the voltage level around the optimum value. Each new cable type must be qualified in a series of tests. This is a very costly procedure, which is only performed when a major step in transmission voltage is required in order to increase the maximum power transfer capability. So far the rated power transfer in the projects, which have been realized with XLPE cables, have only motivated development of cables up to ±320 kV.

It appears that there is no obvious fundamental physical phenomenon which hinders development of cables with higher rated voltage. The electrical field strength in the cable insulation presently is approximately 15 kV/mm, which is far below the withstand capability for the material itself.

A cable pair rated ±800 kV carrying 1600 A would transfer 2500 MW, which will most likely exceed the maximum object rating that can be handled in most power systems.

2.4 Comparison between AC and DC cable transmissions

[Asplund_2004] shows a graph, which is reproduced in Figure 2.2, in which the power transfer capability of an AC cable is compared with a corresponding DC cable having the same stress. In addition curves for AC cables with reduced stress are also drawn. Figure 2.2 shows that "with AC high power can be transmitted short distances or low power long distances. HVDC cables can transmit high power over long distances".

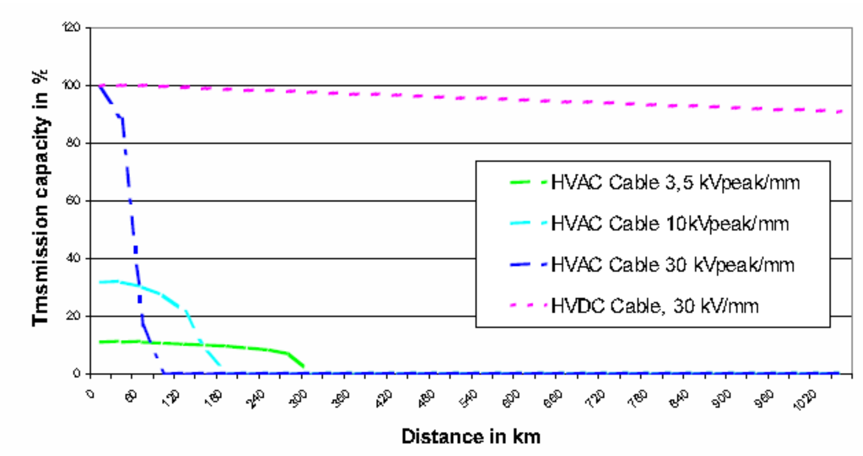


Figure 2.2: Comparison of transmission capabilities of AC and DC cables

(Source: Asplund_2004)

2.5 Gas Insulated Line

The Gas Insulated Line (GIL) concept has been proposed as a means to extend the length of submarine AC transmission and to increase the possible power rating. In this case the solid dielectric insulation in the conventional cable is replaced by gas insulation (SF_6 + nitrogen) in a pipe-line-like structure as shown in Figure 2.3 taken from [Koch_Cigre_2008]. The shunt capacitance in the cable then is dramatically reduced so that longer transmission distances can be bridged. The system can be rated up to 500 kV 4000 A.

Figure 2.3: Outline of a phase conductor for a GIL

(Source: [Koch_Cigre_2008])

Figure 2.4 shows a graph, where overhead lines, XLPE cables and GIL are compared with respect to their transmission capabilities. It is shown that the GIL can be used to transfer high power over long distances.

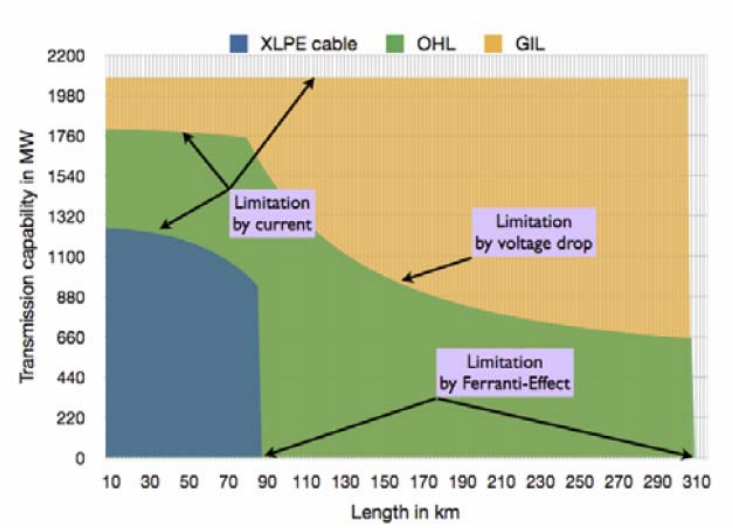


Figure 2.4: Transmisson capability for GIL and different cables

(Source: [Koch_Cigre_2008])

However, the major drawback is the lack of experience for this type of transmission to be used in submarine systems.

3 AC links

Most offshore wind farms built until today are located close to the shore. The transmission distances typically have been less than 100 km. The established power transmission concept in these cases consists of an AC collection grid with rated voltage 20-35 kV and an offshore transformer substation stepping up the voltage to 100 - 220 kV connected to the transmission cable that is connected to the existing power system on the mainland. This concept is illustrated in Figure 3.1.

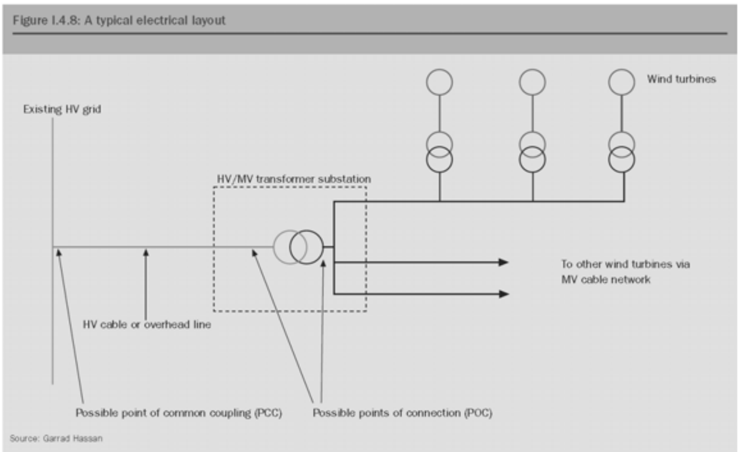


Figure 3.1: Typical electrical layout for wind farm with short transmission distance

(Source: [web_windfacts], chapter 1)

3.1 Literature references

In literature various other proposed systems have been evaluated and compared with the direct AC system. The conclusion in all such investigations is that the AC system remains unthreatened when the distance to shore allows an AC cable connection.

In [Morton_2006] it is concluded that the two-terminal links for the UK Round Two wind farms should be 132 kV AC links, even if DC links also are discussed. However, these are thought to be more expensive.

In [Kling_2006_cigre] it is concluded that two-terminal AC solutions are the most economical solution for interconnection of wind farms.

[Kling_2008] discusses the possibility of taking economical advantage of clustering windparks together with other offshore installations like offshore oil platforms etc. Wind farms have a capacity factor of about 0.3-0.4. If the windpark has a transmission system of its own the same capacity factor is valid also for that system. Thus only half power transmission potential is used. Moreover the life time of the transmission system is twice as long as for the wind farms. The first incentive is to cluster several windparks in the same area to one point and transmit all power from that point to onshore by some means, hvac or HVDC. In Germany it is proposed to build offshore substations to serve as power hubs. Also limits in right-of-way may make it necessary to combine the power from different sources.

Wind speed is correlated in large areas! Clustering of wind power does not necessarily increase utilization of transmission.

AC systems are cheap and reliable however not sufficient for long distance transmission. XLPE for 150 kV is used, 245 kV is available and 400 kV will come.

Several methods to extend the reach of AC systems have been proposed e.g. decease frequency, use multi-phase systems.

HVDC systems using LCC is outruled due to its reactive power consumption (can be alleviated), black start problems, large footprint, commutation failures. VSC-HVDC, although having losses 2% per converter, is seen as the solution.

Multiterminal system using VSC-HVDC is proposed. Voltage droop can be used to share power changes. Finally gas-insulated lines are considered. Have much less capacitance than cables. Filled by low-pressure SF_6. A few onshore applications exist, but none is submarine.

In summary: the most promising option is to combine wind power and oil/gas production.

Reliability aspects have been discussed in some papers.

In [Sannino_2006] three different wind farm layouts with different possibilities to separate faulty parts of the wind farm are compared with respect to expected availability. It is found that ring-shaped string layouts with possibility of infeed from two points are best from an availability point-of-view.

[Underbrink_2006] considers a wind park connected to deliver power through an AC transmission system. Eighty 3 MW windmills are connected to an offshore collection grid at 33 kV. Two main transformers feed a 45 km submarine cable at 150 kV. Three parallel 150 kV land cables takes the power 60 km to the 150/400 kV substation, which is the Point of Common Connection (PCC). It is shown that even though the submarine cable does not have any redundancy the main contribution to the estimated energy not supplied (EENS) emerges from the windmills.

The characteristics of wind farms differs from that of a conventional synchronous generator e.g. with respect to inertia. Therefore the dynamics of the power system is changed when a big wind farm is connected. Some papers address this aspect.

The paper [Ehrlich_2008] deals with the impact of increased wind power generation on the behavior of the interconnected system in steady state as well as during and after a contingency situation. The issues specifically considered are performance during a severe short-circuit and frequency stability after a sudden loss of generation. Especially, the results concerning frequency stability after loss of generation are interesting. It was found that at the conceptual level there are a range of options, e.g. voltage-frequency control, which would place wind generating plants in a position to support system frequency in an emergency situation.

3.2 Conclusion

For power transmission from wind farms sited close to the shore AC cables will be used. It appears that as long as the wind turbines utilize similar concepts as the ones used onshore, i.e. as long as they are designed to be connected directly to a 50 or 60 Hz AC system, there will be little incentive to introduce power electronic devices in the transmission system.

The situation my change if new types of wind generators will be developed, e.g. generators delivering power that is ill conditioned for 50 or 60 Hz networks. However, as long as the market for onshore wind farms is much bigger than that offshore, this is not likely to happen.

4 LCC-HVDC transmission systems

Ac transmission experiences some difficulties related to the parasitic properties, series inductance and shunt capacitance, in transmission lines and cables. DC transmission was developed as a means to overcome these problems, making it possible to realize long distance transfer of large amount of power on over-head lines and to transport power over long submarine cable connections e.g. between mainland and islands. The terminal interface initially was based on converter technology using mercury arc valves, but in the 1970'ies thyristor valves were introduced and they soon outperformed the mercury arc system.

The valves in the converters of this kind can be fired on command whenever the voltage between the anode and the cathode is positive, but once it has been triggered it remains in its conductive state as long as a positive current flows through the device. It can only be brought back to the non-conducting state if the current through the device is eliminated and a negative voltage is applied across the device. These conditions must be provided by the "commutating voltage" in the connected network and accordingly this kind of converter is named "Line-Commutated Converters" (LCC).

The cables used in LCC-HVDC transmission systems use mass-impregnated insulation systems, i.e. insulation based on oil impregnated paper. These insulation system necessitates that the cable has a water-tight cover and therefore such cables have a lead shield both for sea-cable and for land cable. An LCC-HVDC transmission system keeps the current direction but reverses the DC voltage when the power flow direction is changed. Such changes stress the cable insulation, but they can be tolerated by cables using mass impregnated insulation.

The lack of ability to extinguish the thyristor current causes that the LCC converter always consumes large amounts (50% of the converter rating) of reactive power. The converter therefore can only operate if the connected network has sufficient strength. It is necessary that the reactive power compensation can be varied as a function of the power transfer. Further shunt filters are required to sink the harmonic currents created by the converter.

4.1 LCC-HVDC for offshore wind farms

Thyristor based LCC-HVDC is widely used since several decades in power transmission systems, both for transmission on land and for submarine cables. The thyristor has proven to be a reliable and robust work horse in high-power, high-voltage power electronic converters. For transmission using overhead lines the rating exceeding 6 GW at ± 800 kV has been built. For submarine cables ratings about 500 MW at 500 kV have been implemented.

Thyristor-based converters do require reactive power from the connected AC network for commutation. In the offshore network a voltage source that can provide the reactive powers consumed by the LCC-HVDC converter must be established. This can be a rotating synchronous condenser or a reactive power compensator of VSC type (STATCOM). Starting the system from a deactivated state, e.g. after some days without wind, becomes a complicated procedure. Further it is believed that there will be difficulties to fulfil the dynamic requirements related to different grid codes. Another problem may be that the LCC-HVDC system requires a lot of apparatus like filters, shunt banks and breakers. In onshore installations these components are located in a switchyard, but in the offshore applications they must be placed on a platform in the sea.

The main advantage of LCC-HVDC is that the losses in the thyristor converter are small. However, the added STATCOM has fairly big rating and the associated losses must also be taken into account. The importance of the advantage with respect to losses has been diminished after the introduction of multilevel VSC converters.

Another aspect relates to the onshore receiving end of the LCC-HVDC transmission system. When wind power is brought into a receiving network the intention may be that it shall replace existing older (often coal-fired) generation. If so the short-circuit strength will be reduced, when the existing onshore generation is closed down. Therefore, any restrictions on minimal short-circuit power, which may prevent the shut-down of the existing generators, are most unwanted.

4.2 Literature references

[Li_2007] deals with a LCC-HVDC system having a STATCOM in the offshore network. The paper describes the frequency control in the offshore network, which is determined by the wind speed as indicated in Figure 4.1. It has been shown that the system can successfully ride through a receiving end grid fault.

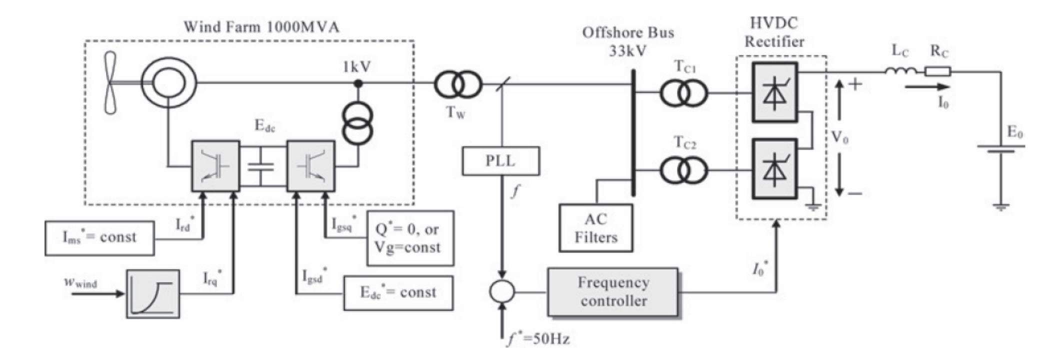


Figure 4.1: Power System model for PSCAD simulations

(Source: [Li_2007])

[Foster_2008] discusses a LCC-HVDC arrangement. A 500 MW wind farm has a STATCOM of 150 MVA at the offshore side and is connected through a 500 kV DC cable to the receiving station on mainland as depicted in Figure 4.2. The rectifier+STATCOM is one unit that is operated to control the DC voltage by changing the current reference. The DC voltage in STATCOM is used to determine the DC current order for the rectifier. It acts as an infinite AC source that is controlled by the real current component, which is derived from the wind speed.

The paper describes a method to handle AC side faults in the connected onshore grid. The method utilizes a frequency increase on the STATCOM as the means to reduce the DC voltage level in the STATCOM. This is better than relying on telecom reference signals coming from the mainland, when a fault has been detected. The overvoltage is reduced from 3 pu at constant frequency to 1.8 pu during a 3-phase fault on the onshore grid.

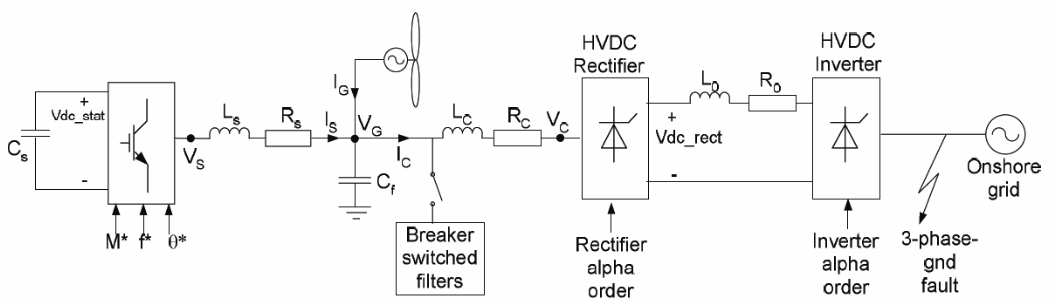


Figure 4.2: LCC-HVDC system with offshore STATCOM

(Source: [Foster_2008])

Similar results are obtained in [Bozhko_2008]. The rating of the STATCOM is discussed and it is shown that the rating depends on the telecommunication delays at faults on the mainland side as depicted in Figure 4.3.

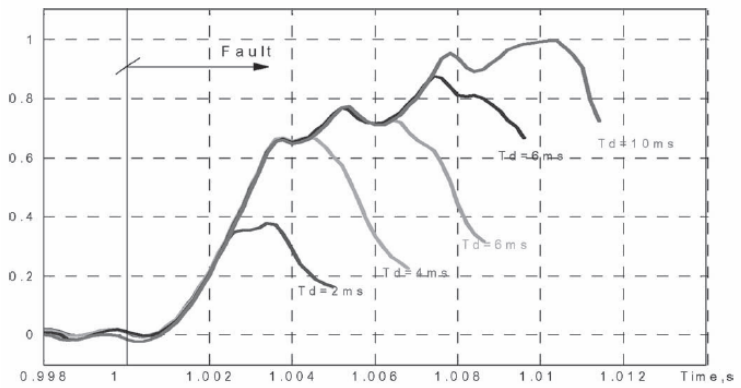


Figure 4.3: STATCOM rating versus telecommunication delay

(Source: [Bozhko_2008])

[Zhou_ICEMS_2008] proposes a topology according to Figure 4.4, where an LCC-HVDC is combined with a STATCOM at the offshore terminal and an IGBT Current Source Inverter (CSI) is connected in the onshore receiving station, which is connected to the AC network.

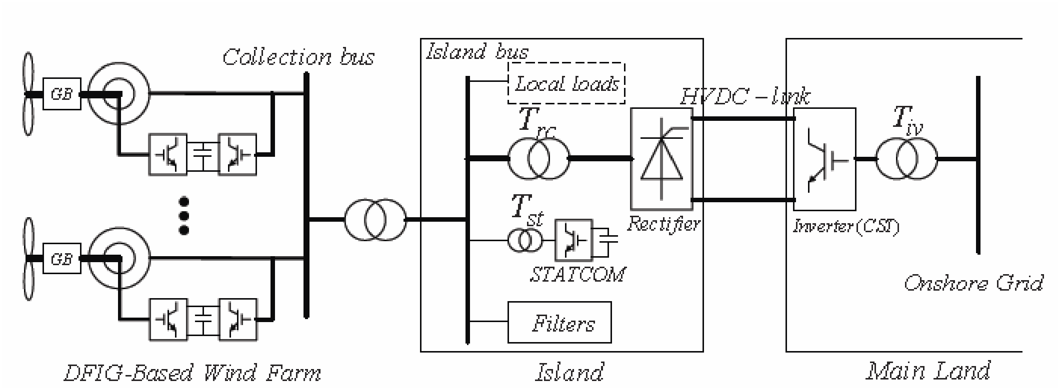


Figure 4.4: Hybrid HVDC topology for DFIG-based wind farm

(Source: [Zhou_ICEMS_2008])

The advantages of this approach are that it has black-start capability and that it can provide independent reactive control for the grid like the VSC-HVDC system. It can however be noted that the CSI converter would need valves having symmetrical blocking capability. Suitable semiconductors of this type are not available and therefore such valves must be implemented by IGBT-components in series with a diode.

4.3 Conclusions

Many studies have investigated the LCC-HVDC system using STATCOM as a voltage source in the offshore network. It is shown that a fault in the onshore network seems to have been the most challenging problem, specifically for the design of the STATCOM. Black-start is another concern.

However, even if solutions to these problems can be presented, the main problem remains, namely that it appears that the LCC-HVDC solution has a fairly complicated main circuit including both the line-commutated converter, a STATCOM of considerable rating and filter banks etc.

The losses in the LCC-HVDC are assumed to be small, but improved VSC-HVDC systems has made this aspect less important.

5 VSC-HVDC with 2- or 3-level technology

In the late 1990'ies the first Voltage Source Converter (VSC) based HVDC transmission system was installed. The valves in the VSC utilize semiconductors that can be turned-on and turned-off at command, namely Insulated Gate Bipolar Transistors (IGBT). This makes commutation of the converter valves independent of the connected network. The reactive power exchange with the network then can be controlled and used to support the power system when needed.

Contrary to the LCC-HVDC the DC voltage polarity remains constant irrespective of the power transfer direction and the current direction changes when the power flow reverses. The elimination of the requirement for voltage reversal opens up the possibility to use cables with polyethylene cross-linked (XLPE) insulation. The benefits of this have been described in chapter 2. It also becomes simpler to implement multi-terminal HVDC systems if the polarity and voltage level are kept constant.

The development of VSC-HVDC triggered a fast development of offshore HVDC applications for the oil and gas industry and wind farms.

The most important factor for favouring VSC-HVDC before the LCC-HVDC system is that it can independently control the active and reactive power exchange between the converter and the connected network. The converter thereby becomes much less dependent on the status of the connected AC network. Commutation failures can be avoided and features like black-start can be implemented.

The VSC-HVDC system utilizes less external apparatus and therefore has a smaller footprint than its LCC-HVDC counterpart.

Existing VSC-HVDC systems operate at DC voltages up to ±150 kV and are based on the conventional 2- or 3-level VSC converter concept as shown in Figure 5.1, which depicts a 2-level converter.

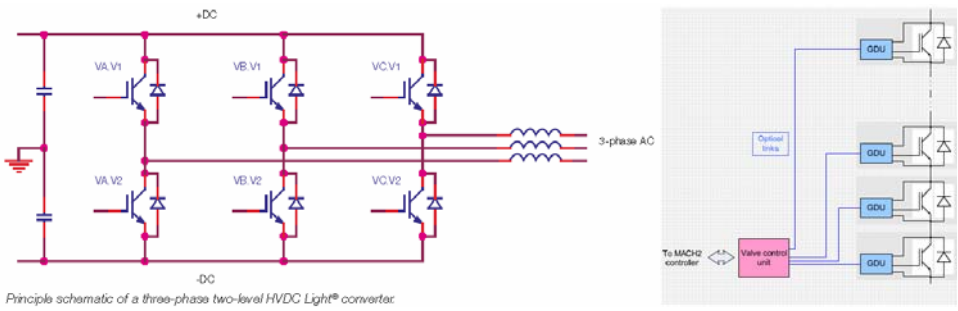


Figure 5.1: 2-level VSC converter, six-pulse bridge (left), implementation of each valve (right)

(Source: ABB)

A large number (hundred) of IGBT devices are connected in series in each arm. They are commanded to switch simultaneously with very high precision in time (fraction of µs). The high DC voltage and the very fast switching of the IGBTs create an extremely high voltage derivative, which stresses the phase inductor connected in series with the converter terminal and which also causes electromagnetic interference (EMI).

It is necessary that the series-connected IGBTs devices in the valves have been designed so that they appear as a short-circuit in case of failure. Otherwise an arc will be created in the encapsulation, which may cause an explosion. By special encapsulation of the IGBT chips arcing will be avoided ("short-circuit failure mode").

The output voltage is synthesized using pulse width modulation (PWM) technique. An example of switching pattern for this kind of converter is shown in Figure 5.2. It can be seen that in this example 23 turn-on operations are executed per network cycle. The corresponding device switching frequency becomes 1150 Hz in a 50 Hz network.

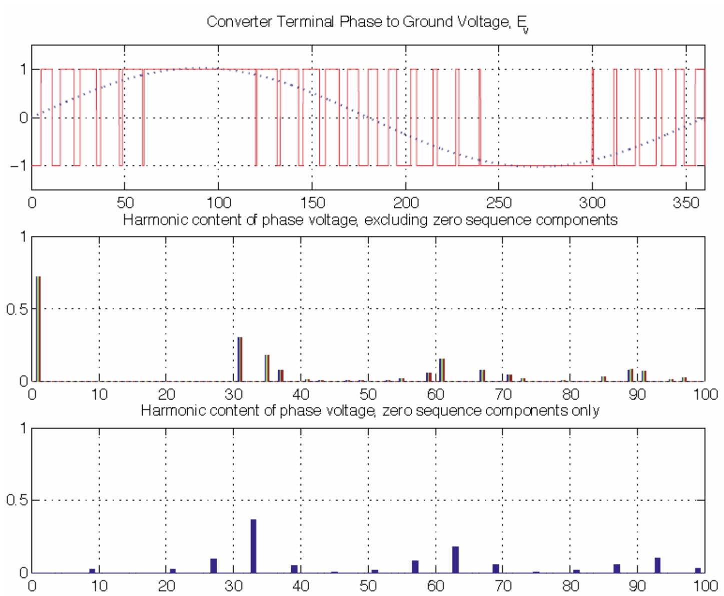


Figure 5.2: Example of switching pattern for a 2-level VSC-HVDC

(Source: ABB)

The high switching frequency causes substantial losses in the converter. The losses, calculated according to IEC 61803 amounts to approximately 1.6% of the rated HVDC transmission capacity (per station) at rated load. The no-load (standby) losses are approximately 0.2%. The main contributors to these losses are the IGBT valves (≈1.1%), the converter transformers (≈0.21%) and the converter reactors (≈0.12%). The rest originates from the AC filters, the station service power, and the DC capacitor.

Since 1999 ABB has made about ten installations of VSC-HVDC for cable transmission. One installation has also been made for over-head line transmission. All installations utilize 2- or 3-level VSC converters.

The first offshore wind farm VSC-HVDC project, the BorWin 1 [web_borwin1], was commissioned during 2009. Rating is 400 MW at ±150 kV. Cable lengths are 2×128 km (submarine) + 2×75 km (underground). An outline of the converter hub platform is shown in Figure 5.3. It illustrates the large dimensions of the mechanical arrangements involved. E.g. the transformers only occupy a quite small area on the platform.

Figure 5.3: Outline of the offshore terminal for BorWin 1 (1 AC power area, 2 converter reactors, 3 HVDC valves, 4 DC power area, 5 cooling system)

(Source: ABB)

6 VSC-HVDC using Multilevel technology

Until today the only VSC-HVDC main circuit topology, that has been in use, is similar to that used in industrial or traction frequency converters, i.e. 2- or 3-level PWM converters. However, some years ago, an alternative VSC-HVDC solution was suggested by Allebrod, Hamerski and Marquardt [Allebrod_2008]. The circuit, which is based on series-connection of sub-modules containing a semiconductor switch and a capacitor, was first suggested by Marquardt and Lesnicar [Lesnicar_2003] and is commonly referred to as Modular Multilevel Converter (M2C). The main circuit arrangement is outlined in Figure 6.1. The first installation for a transmission application presently is under commissioning [Westerweller_2010]. Moreover, this kind of VSC converter will be utilized for many other high-voltage, high-power applications beside the VSC-HVDC, e.g. STATCOM, railway power supply and for large motor drives (tens of MW).

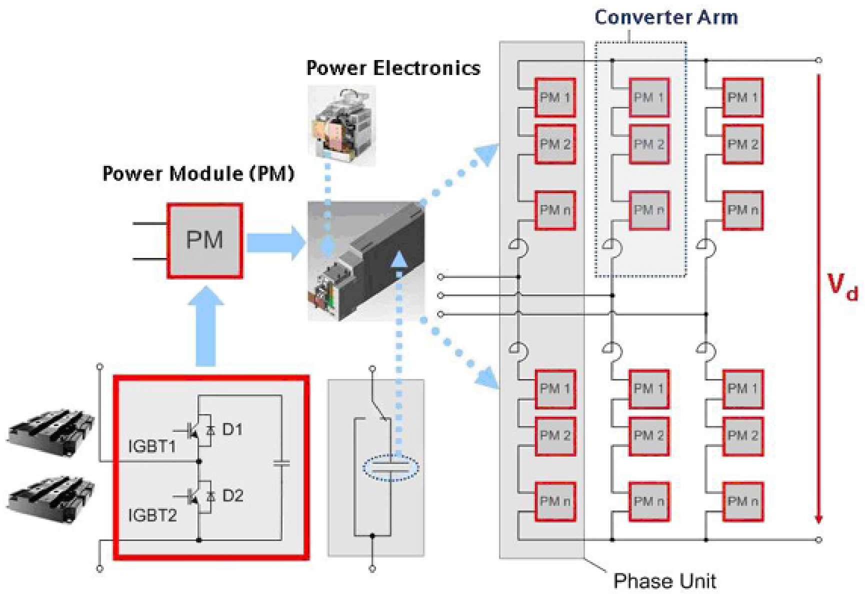


Figure 6.1: Main circuit of a Modular Multilevel Converter (M2C)

(Source: Siemens)

Each arm contains a series-connection of sub-modules, each one comprising a DC capacitor and a half-bridge as shown to the left in the figure. The function of the half-bridge is to insert or bypass the sub-module capacitor in the chain of series-connected sub-modules as it is indicated in the functionality sketch beside the sub-module schematics. The control system keeps the average of the *sum of the number of inserted sub-modules* in the upper and the lower arm at a constant level in order to *balance the applied DC voltage*. The desired *potential of the AC terminal* is synthesized by varying *the difference* *between the number of inserted sub-modules* in the upper and the lower arms. Figure 6.2 shows this functionality and the resulting output voltage waveform.

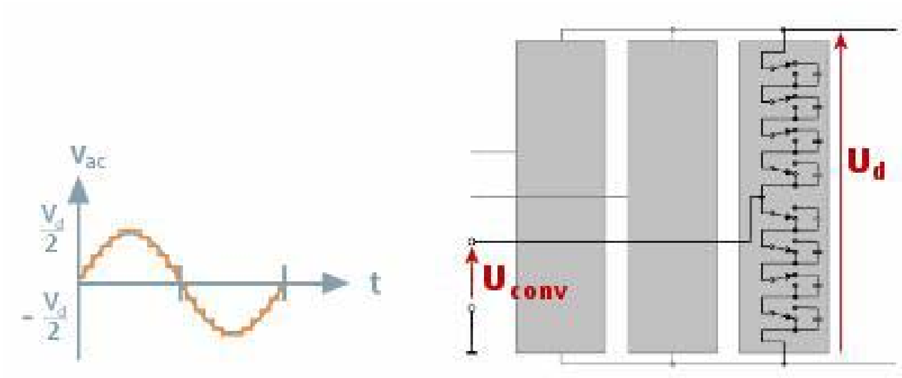


Figure 6.2: Functional diagram of the M2C converter and the AC side waveform

(Source: Siemens)

In the M2C, contrary to the switching operations in the 2-level converter, each step in the output waveform results from switching only of one sub-module in each arm and accordingly it involves only a small portion of the semiconductor devices in the arm. The average switching frequency *per device* therefore can be dramatically reduced as compared with the 2-level converter. Typically the switching frequency is 150 Hz per device. The harmonic content of the produced waveform at the same time is very small, so only very small filters are necessary.

Certainly the number of semiconductor positions in the M2C is higher than in the 2-level converter. However, the total silicon area does not differ significantly [Allebrod_2008]. Due to the reduced switching frequency the total loss per converter is approximately 1.0% at full load.

The stress of the inductors in the M2C circuit is much milder than in the 2-level converter due to the smaller step-heights.

The basic control problem in the M2C is to make sure that the capacitor voltages in all the sub-modules are strictly controlled in order to avoid overvoltage. Different manufacturers apply different principles and information about such details normally is not public. The same thing applies for converter protection methods.

The development of the M2C converter with respect to topology, control and protection has just begun and it offers a vast field for research both in industry and academia.

6.1 Siemens implementation

Siemens was the first company to introduce the M2C technology. Siemens is also holder of a number of patents regarding M2C. Their idea is to use standard industrial grade IGBT modules with plastic cases. In Figure 6.3 such an IGBT module is shown.

Figure 6.3: IGBT module for Siemens M2C

(Source: Siemens)

The sub-module is a half-bridge sub-module equipped with a bypass thyristor and a bypass vacuum switch. In Figure 6.4 a schematic diagram of a sub-module is shown.

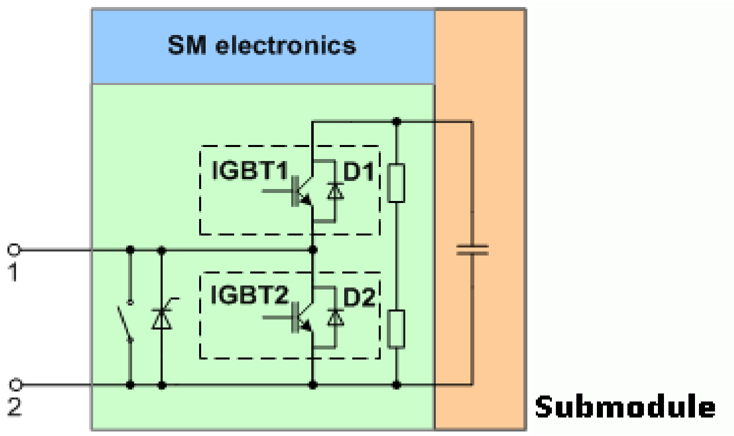


Figure 6.4: Schematic diagram of a sub-module

(Source: Siemens)

A converter arm is formed by stacking a sufficient number of sub-modules. For HVDC applications each arm has a number of sub-modules of the order of 100, depending on the rated voltage on the DC-side. In Figure 6.5 it is shown how the sub-modules are stacked in order to obtain a converter arm.

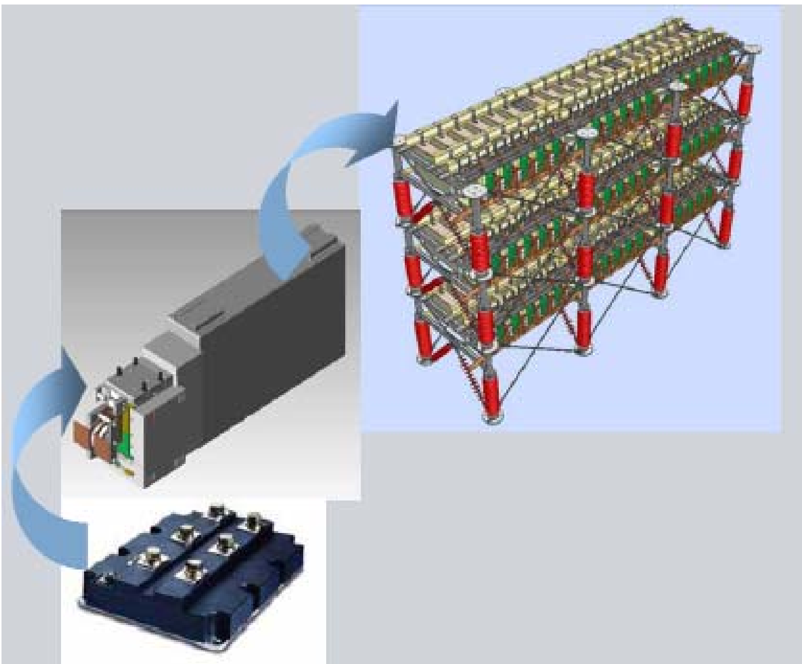


Figure 6.5: IGBT module, submodule, and converter arm of an M2C

(Source: Siemens)

Siemens was the first company to win an order of an HVDC link using M2C technology, the Trans Bay HVDC Link in the San Francisco area, see Figure 6.6. The operation will start during 2010.

Figure 6.6: The Trans Bay HVDC Link

(Source: Siemens)

6.2 ABB's implementation

Lately (July 2010) ABB was rewarded a contract for a new offshore wind farm plant, "DolWin 1". The rating for that plant is 800 MW at ±320 kV. Cable lengths 2×75 km (submarine) + 2×90 km (underground). This installation shall be commissioned in 2013.

One interesting feature with this installation is that it will initially serve one 400 MW wind farm, but additional wind farm(s) will be connected later.

A paper [Jacobson_2010] presented in the Cigré Session 2010 indicate that ABB will utilize a kind of multilevel converter, called Cascaded Two-Level (CTL) converter, in the development of the VSC-HVDC for ±320 kV. Figure 6.7 shows the main circuit of this converter.

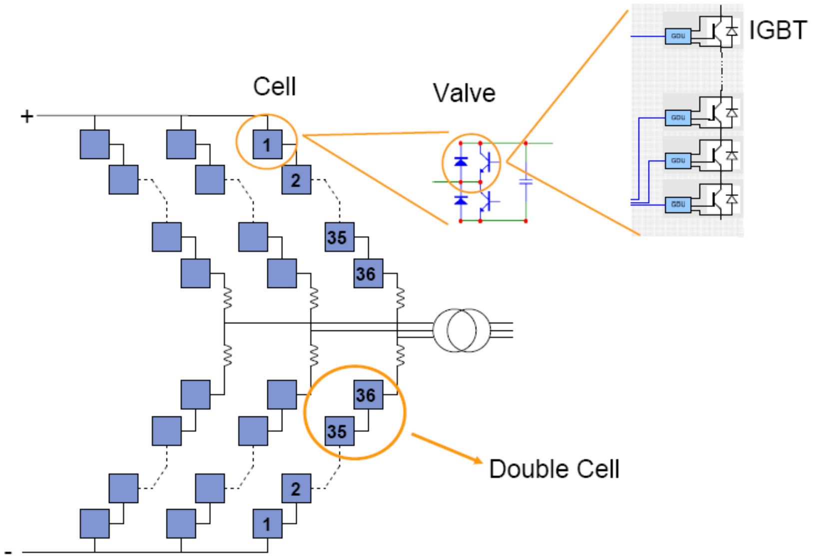


Figure 6.7: Outline of the CTL converter

(Source: ABB)

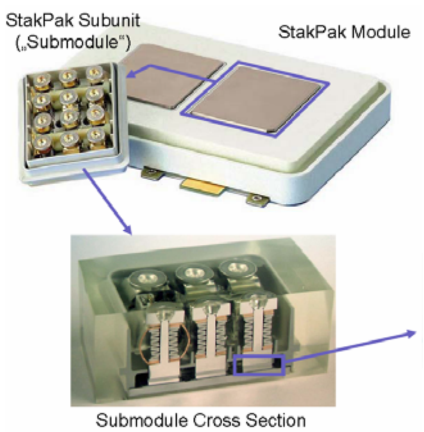


Figure 6.8: Design of IGBT with short-circuit failure mode

(Source: [Jacobson_2010])

In the CTL converter the half-bridges in the sub-modules comprise strings of a fairly low number (about ten) of series-connected IGBTs. The reason for this choice relates to protection issues as described in [Jacobson_2010]. The IGBTs are of press-pack type having short-circuit failure mode. Figure 6.8 shows the design of such components. It can be seen that each chip is contacted by an individual pressure spring arrangement rather than through bond wires.

The mechanical design of the sub-module is shown in Figure 6.9.

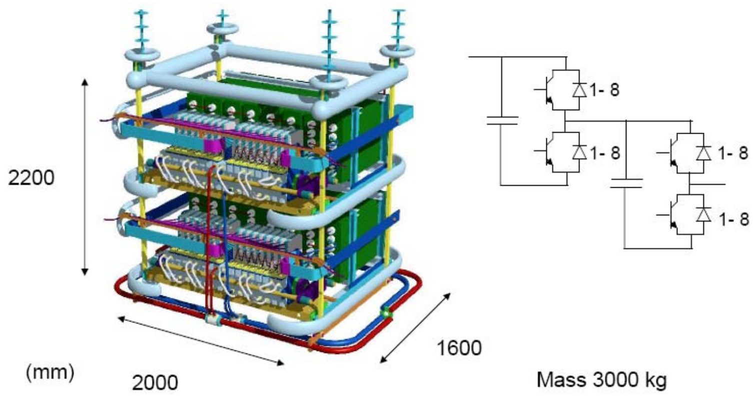


Figure 6.9: Mechanical outline of a CTL double sub-module

(Source: ABB)

Figure 6.10 shows the artist's vision of a future VSC-HVDC station. It can be seen that the idea is that in future VSC-HVDC stations most of the external passive components like filters, reactive power compensation devices etc. shall be replaced by improved functionality of the power electronics. Thereby a lot of switching devices like breakers, disconnectors etc will be removed from the switchyard making the installation compact and clean. At the same time the performance of the VSC-HVDC system will be improved making it applicable in a wide range of situations without a lot of engineering efforts.

Figure 6.10: Artist's view of future VSC-HVDC installations

(Source: ABB)

6.3 Alstom Grid's implementation

Alstom Grid is promoting a variant of M2C with sub-modules consisting of full-bridges. The IGBT is a commercially available device with a voltage rating of 3,3 kV. The nominal switching current of the device is 1500A. In order to accommodate for safety margins, the device is typically operated at a direct voltage of 1,8-2.0 kV and a current of 1000-1200A. Connecting a number of such modules in series, as shown in Figure 6.11, creates the chain link, or multilevel circuit, which allows the converter to create a controllable AC voltage waveform in both magnitude and phase angle at each terminal of the HVDC transmission scheme.

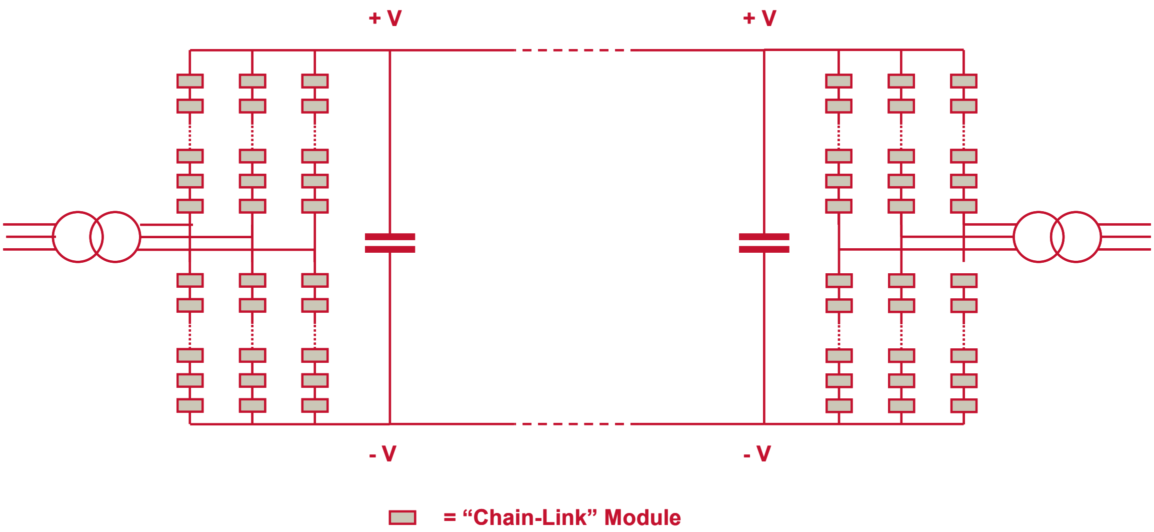


Figure 6.11: Multilevel converter arrangement

(Source: Alstom Grid)

By controlling the switching instants, both turn-on and turn-off for each module, a stepped AC voltage waveform is created from the individual DC charged capacitors. In an off-shore wind farm application with a DC-side voltage of approximately 200-400 kV, there would be several hundred sub-modules in series, and thus the voltage waveform would be virtually sinusoidal. With this multilevel converter topology a voltage waveform is created which is sufficiently sinusoidal to avoid the need for any additional harmonic filtering on the AC side. This provides a considerable advantage in cost and space requirements, especially for an off-shore installation.

The power electronic unit is built into a single sub-module, as shown in Figure 6.12 (taken from [MacLeod_EPE2010]), which contains the IGBTs, mounted on water cooled heat sinks, the DC capacitor (oil free design), the gate drive card for the IGBTs and a fast acting mechanical by-pass switch, which short circuits the level in the event of an IGBT failure to open circuit. The complete sub-module is 1500mm (l) x 650mm (h) 300mm (d) and has a mass of 165 kg. Eight sub-modules are mounted in a rack to form a complete power module. These modules are mounted in vertical or horizontal configurations as dictated by the available space. On an off-shore platform, floor area may be the key factor, while height of the building may be less critical. For the onshore station the reverse may be true. By using a scalable modular concept the VSC converter can be adapted to any requirement. The power module assemblies are suitable for floor mounted or suspended applications, depending on the mechanical forces to which the structure will be subjected. For an off-shore installation a suspended structure may be more suitable to withstand the continual low scale movement imposed by wind and wave forces. In some cases an active damping arrangement may be required on the structures to limit undue wear on the suspension joints.

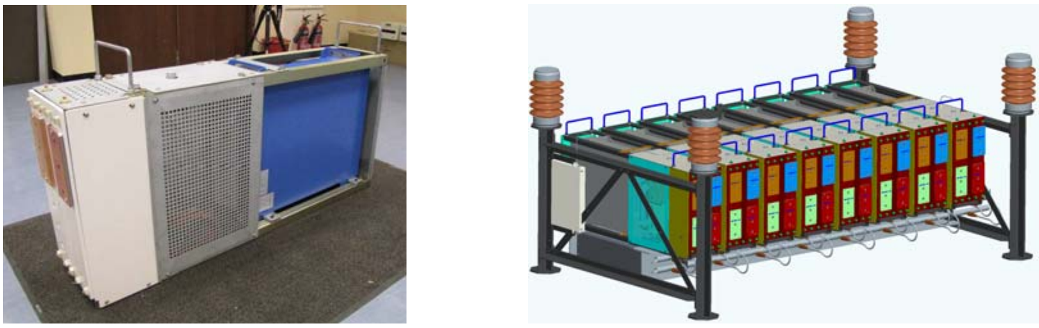


Figure 6.12: Single sub-module (left) and a complete power module (right)

(Source: [MacLeod_EPE2010])

The use of the more costly full-bridge sub-modules appears to be somewhat surprising, as there is usually no need to operate the arms with both positive and negative voltage. If the operating conditions of the switches in the sub-modules are investigated it is found that the stresses are quite unevenly distributed among the switches during normal operation. An explanation to the choice of full-bridge sub-modules is that Siemens has several patents covering the solution with half-bridges. Alstom grid also claims that they use this topology because it offers the possibility to reverse the voltage on the DC-side, so that it can operate together with a thyristor-based LCC-HVDC. Another benefit with the full-bridge technology is that it is possible to handle short-circuits on the DC side very effectively. This may be very valuable if a meshed HVDC grid is formed.

6.4 Comparison of the different implementations

The three concepts from the manufacturers Siemens, ABB, and Alstom Grid rely on the same basic idea. The ABB solution using series-connected press-pack IGBTs in a half-bridge connection has basically the same operational characteristics as the original idea by Marquardt and the implementation by Siemens, but faults are handled in a different way. Based on the knowledge available today it is impossible to evaluate which of the technologies is superior from a fault-handling point-of-view. Alstom Grid has not clearly indicated in what direction to proceed, but the official message is to use full-bridges for the sub-modules.

In normal operation, this means a substantial over-investment in switching semiconductor components, and further increased losses. However, some extra features will be obtained. The converter can operate with reduced and even reversed DC voltage, so that it can operate together with a classical HVDC. Moreover, in case of a short circuit on the DC-side the AC side can be effectively separated from the faulty DC side.

The alternative double clamp sub-module suggested in [Marquardt_2010] has not been particularly promoted by any of the three manufacturers.

In Table I an attempt to compare the three technologies is made. For all three technologies the output voltage is excellent and efficiency well above 99% is anticipated.

Regarding the availability it is very difficult to give definite answers. Due to the modularity, a certain redundancy can be introduced. Knowing the availability of a single sub-module, it is possible to determine the change in availability by adding an additional sub-module. In this way a trade-off between availability and cost can be made in the design stage. However, as for all other new technologies it is likely that the first projects will suffer from typical problems of new technologies. These may seem to be considerable initially, but as time goes these problems will be solved.

Cost is always hard to estimate for new technologies, mainly due to high development costs and to risks with new technologies. It is therefore hard to draw any final conclusions regarding the relative cost for the three technologies. Probably, the cost for the customer in the first stages of market introduction will be based mainly on the effect of competition. However, in a later stage the full-bridge version will inevitably be more costly. Exactly how much more costly the full-bridge alternative will be is hard to evaluate.

In all cases there is a considerable potential for cost reductions in the future. In all three cases the main circuit is dominated by semiconductor components and capacitors. Both these components have shown a monotonically decreasing cost over time.

Regarding the potential for meshed HVDC grids the full-bridge sub-module has a considerable advantage over the half-bridge as the AC side can be separated from the DC side in case of DC-side faults. However, in case half-bridge sub-modules are used in conjunction with semiconductor circuit breakers, the same or even better fault-handling properties can be obtained but with a considerably increased cost compared to the case without DC circuit breakers. Exactly how this should be realized in the future remains to be seen. This requires a thorough investigation which is far beyond the scope of this report.

Table I: Comparison of three different multilevel VSC-HVDC technologies

Manufacturer	**Siemens**	**ABB**	**Alstom Grid**
Sub-module technology	Half-bridge	Half-bridge with series-connected switches	Full-bridge
Alternating voltage waveform	++	++	++
Efficiency	++	++	+
Availability	++	++	++
Cost	+/-	+/-	-
Potential for future cost reductions	+	+	+
Potential for meshed HVDC grids	+	+	++

7 Collection grids

7.1 Ac collection grids

In most installations a normal AC collection grid is used. The voltage level normally is 20-30 kV. Whenever a direct AC cable connection is used and the wind turbine generators are short-circuited or doubly-fed induction generators the collection network must use the network frequency, i.e. 50 or 60 Hz. However, when the wind farm is connected through an HVDC system to the onshore network, the frequency in the wind farm can be freely selected. It may also be controlled depending on the average wind speed.

In order to keep the offshore systems as similar as the (much more common) onshore systems, the collection grid of the offshore systems will also normally operate with a frequency of 50 or 60 Hz.

The generators are rated in the range 2-5 MW. The optimal voltage level, from efficiency weight and cost perspective, for such machines is far below the rated voltage for the collection grid. Accordingly transformation between the generator voltage level and the collection voltage level normally will be required.

It should be noted that it is possible to manufacture a generator that delivers DC voltage (after rectification) at voltage levels that could be used in the collection grid. However, such machines become heavier than machines with lower voltage.

7.2 DC collection grids

Some authors have proposed the use of DC collection grids. One driving force is to avoid large transformers on the offshore platforms. In [Meyer_IAS_2007] the use of DC collection grids in large windfarms is proposed to cut costs. DC/DC converters then become necessary to achieve different voltage levels. Three-phase series resonant converters using GCT (Gate Commutated Thyristors) combined with amorphous metal transformers are being proposed and investigated. It is shown that a 3-phase 50 MW DC/DC converter operating at 1 kHz has an efficiency of 99%, which is claimed to be higher than a conventional AC transformer. A solution for making the DC/DC converter bidirectional with 0.5% power capability in the reverse direction also is proposed (mechanical connection of phase b and c, antiparallel thyristor string in phase a).

The collection grid DC voltage will be much lower than the transmission DC voltage, requiring the use of DC/DC converters to step up the voltage level from the collection grid rated voltage level to the transmission voltage level. Two drawbacks exist with this solution:

- power conversion takes place in several steps, causing extra loss
- high-power transformers using elevated frequency must be developed

In some papers [Carlsson_2005], [Max_2007] it is proposed to series-connect the (rectified) output voltage from several generators in order to reach the selected transmission DC voltage level. It is anticipated that the isolation is taken care of by AC or DC transformers in the wind turbines. The benefit is that the whole offshore converter platform would be avoided.

7.3 Conclusion

The arguments for DC collection grids given in the papers are not convincing. The DC/DC converter losses most likely are higher than the losses in a 50 or 60 Hz transformer. The weight of the transformers certainly is significant, but the transformers are quite small when compared with the whole platform, see Figure 5.3.

A DC/DC collection grid further requires that a DC/DC converter is included in each wind turbine. It appears that it would be a significant complication to install such a device in the nacelle due to the space required for safety reasons (see interview in 14.2.2).

8 DC Grids

It has been mentioned that many initiatives are pushing the idea of establishing a SuperGrid that shall allow renewable power production to connect to the big load centres. One example, shown in Figure 8.1, has been taken from [web_oceangrid].

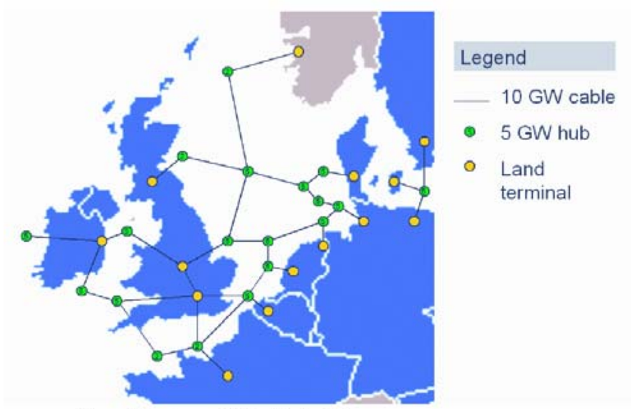


Figure 8.1: One proposal of an Ocean Grid for the North Sea

(Source: Leonardo energy)

8.1 The branches in the network

Note that the ratings of these super-grid cable transmission systems is assumed to be very high, 10 GW. Presently, submarine XLPE-cables rated for ± 320 kV with a 2800 mm^2 Cu conductor can transfer 1200 MW [abb_brochure]. However, it appears that there does not exist any physical reasons that would make it impossible to increase the rated voltage substantially.

In any case it can be concluded that such a SuperGrid needs several parallel large cables in order to provide the desired power transfer capability.

The newly placed orders for the offshore converter stations DolWin Alpha, HelWin Aplha will serve several wind farms. This might be seen as a first step to establish offshore connection points in the sea.

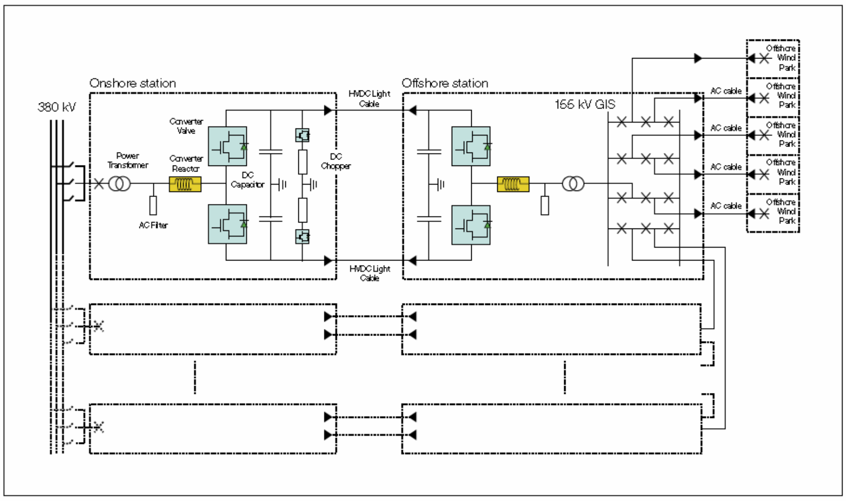
8.2 Connection between the branches

In order to establish a *meshed* DC grid many new questions related to operation and protection must be solved. Like in an AC network it is necessary that each single branch can be isolated in case of a cable failure. In case of a fault in a large DC network the current will increase monotonically with a high derivative. The isolating switches must react in few ms in order to avoid that the current becomes too high (hundreds of kA). The obvious solution, which is available already today, is to build breakers based on semiconductors. The added loss is just a fairly small portion of the loss in a converter. A major challenge is to detect when a failure occurred and determine which breakers that shall operate.

8.3 DC grids - in the research community

It is obvious that questions related to DC grids begins to appear in the literature. E.g. in the last Cigré session a paper, [Asplund_2010], discusses power flow calculation and control and another paper, [Yao_2010] proposes a control approach based on coordinated DC grid management using close-loop DC voltage control and DC droop characteristics, to ensure smooth system operation and proper power sharing among various DC converter stations. The proposed system achieves accurate DC voltage regulation and power sharing. It also provides significant damping and stability support to the onshore power networks after AC fault.

It can also be noted that the subject is also mentioned in the manufacturer's documentation [abb_offshore] as shown in Figure 8.2, which indicates the possibility to assemble several converters at the same location.



The converter stations can be prepared for future expansion of capacity.

Figure 8.2: Possible future expansion of the transmission facility

(Source: ABB)

To conclude it is obvious to us that many factors coincide which makes it likely that DC grids will be realized in a (relatively near) future if the idea gains sufficient political support:

- several manufacturers agree on a similar HVDC concept, namely the modular multilevel converter
- several cable manufacturers work on similar approaches

- big converter hubs will be built and commissioned during 2013
- there does not seem to be any obvious physical obstacles that can prevent the desired power handling capability to be met
- the research community is enthusiastic and shows a lot of interest
- many lobby groups are actively promoting the concept

9 Important projects

9.1 BorWin1

[web_borwin1] gives some data for the newly commissioned HVDC hub BorWin1, which is also depicted in Figure 9.1. The converter is of 2-level type PWM-modulated. The data for this transmission link are:

Power:		400 MW		
DC voltage:		±150 kV		
AC voltage:	platform	170 kV	onshore	380 kV
Length:	submarine	125 km	underground	75 km
Cost:		> 400 M$		
Manufacturer:		ABB	Commissioning:	2009

Figure 9.1: BorWin 1 offshore HVDC hub

9.2 Trans Bay HVDC project

The Trans Bay project in San Fransisco, USA, is the first HVDC project utilizing the multilevel converter technology. It is described briefly in [Westerweller_2010]. The following data apply:

Power:		400 MW		
DC voltage:		±200 kV		
AC voltage:	Pittsburg	170 kV	Portrero	115 kV
Length:	submarine	86 km		

Manufacturer:		Siemens	Commissioning:	2010

9.3 HelWin1

Power:		576 MW		
DC voltage:		±250 kV		
AC voltage:	platform	155 kV	onshore	380 kV
Length:	submarine	85 km	underground	45 km
Cost:		500 M€	only cable	150 M€
Manufacturer:		Siemens	Commissioning:	2013

9.4 DolWin1

Power:		800 MW		
DC voltage:		±320 kV		
AC voltage:	platform	155 kV	onshore	380 kV
Length:	submarine	75 km	underground	90 km
Cost:		700 M$		
Manufacturer:		ABB	Commissioning:	2013

9.5 BorWin2

Power:		800 MW		
DC voltage:		±300 kV		
AC voltage:	platform	155 kV	onshore	400 kV
Length:	submarine	125 km	underground	75 km
Cost:		500 M€	only cable	200 M€
Manufacturer:		Siemens	Commissioning:	2013

10 University research projects in Sweden

10.1 Chalmers

10.1.1 Stefan Lundberg (PhD 2006)

Lundberg has investigated the design and control of a wind farm utilizing series-connected wind turbines with a DC output. The system layout is presented in [Carlson_2005]. Lundberg states that a direct voltage that is suitable for HVDC transmission can be achieved without a centralized DC/DC converter. It is found that it is necessary to design the individual wind turbine converters for a voltage level of about 35% higher than the nominal voltage. Otherwise there will be a substantial energy loss due to the uneven power production from the individual wind turbines that occurs in actual installation. In addition, it is claimed that the series DC wind park has a good economical potential, since it eliminates the need for an offshore platform in the wind park. Even if the latter is true, a serious drawback with the suggested wind farm concept is that all wind turbines have to be designed for the transmission voltage level. It is, therefore, the opinion of the authors that such systems are not likely to find a widespread acceptance.

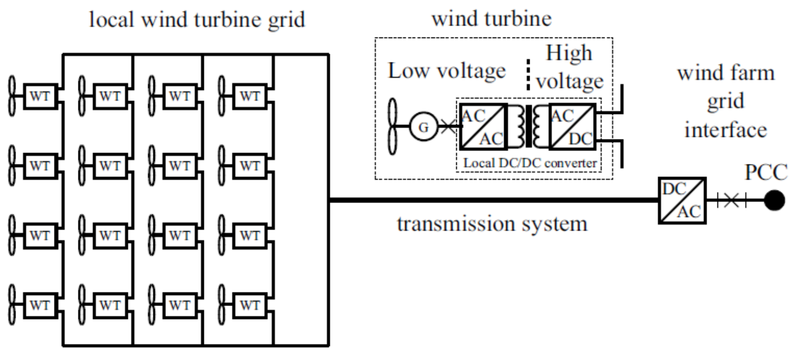


Figure 10.1: Wind farm layout with series connected wind turbines

(Source: [Carlson_2005]).

10.1.2 Lena Max (PhD 2009)

Max investigates the design and control of a wind farm with an internal DC grid as proposed in [Max_2007]. The purpose of using an internal DC grid in the wind farm is to decrease the cost since DC cables are cheaper than AC cables and the transformers in DC/DC converters are much smaller than 50 Hz transformers. The aim of the project was to investigate the control of the internal voltage levels in the DC grid and also the control of the wind turbine generators, as well as the choice of voltage levels and grounding system.

Special attention is given to the design of the DC/DC converters. Three converter types are investigated and evaluated and the preferred type is stated to be the full-bridge DC/DC converter. Although the analysis made is of a high standard, the wind farm concept is not entirely convincing. The main reason is that unnecessarily many conversion stages are used. This means that it will be hard to achieve a competitive efficiency and that the cost savings for the cheaper DC cables and small high-frequency transformers are more than compensated by the cost for the two DC/DC conversion stages.

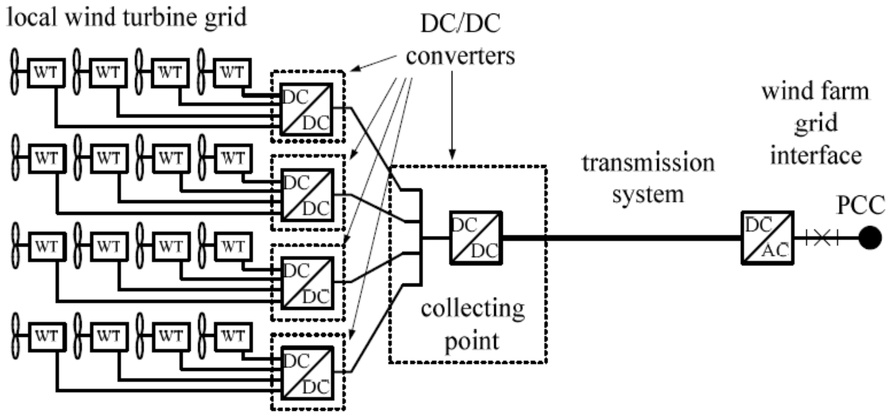


Figure 10.2: Wind farm layout with a DC collection grid

(Source: [Max_2007])

10.2 Lund university

Industrial Electrical Engineering and Automation (IEA) conducts research on design and operation of offshore power systems based on multiterminal HVDC systems. The research deals with ancillary services provided to the connected wind farms, the connected AC networks and transmission services through the HVDC networks. These studies have just been started up.

10.3 Royal Institute of Technology

10.3.1 Laboratory for Electrical Power Systems

Research on multiterminal HVDC dynamical interaction between DC and AC networks.

10.3.2 Stephan Meier (PhD 2009)

In contrast to many other suggested wind farm concepts, Meier suggests a layout with a medium-frequency (approx. 500 Hz) collection grid [Meier_2009]. The strengths of the idea are that thyristor-based bridges can be used as inverters in the wind turbines and that all switching transitions in the system are soft. Additionally, the transformers are considerable smaller than in the case of a 50 Hz collection grid. The commutation voltage for the thyristor bridges is created by a single-leg VSC at the sending end of an HVDC transmission. As there are few conversion stages and as all switching transitions are soft very high efficiencies can be obtained. The cost is also reasonable because of few conversion stages and because the transformers are comparably small. A serious drawback with the suggested system concept is that resonances are inevitably created in the cables of the collection grid. Due to the slopes of the VSC-voltage transients are generated each half cycle of the collection grid voltage. Several attempts were made to find simple solutions to this problem, but no simple solutions could be found. Even though, it might be possible to find acceptable solutions to the collection-grid resonances in many cases it is not likely that the proposed system would gain widespread acceptance.

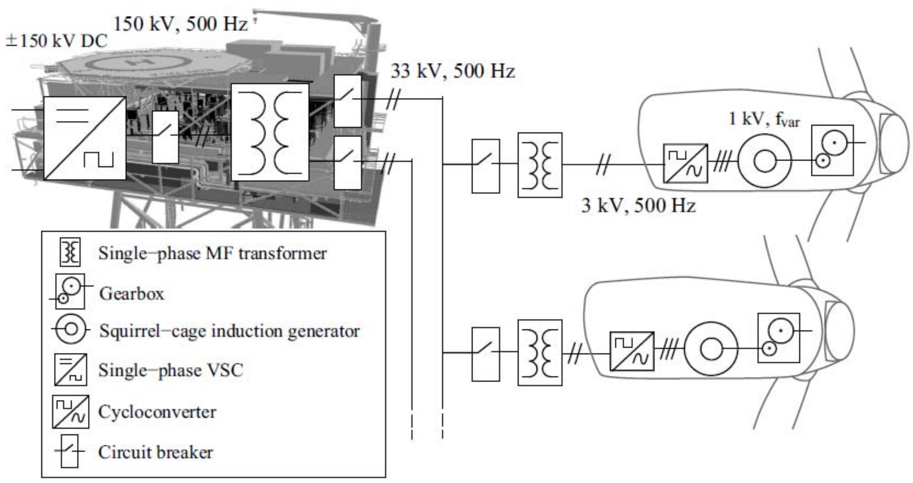


Figure 10.3: Wind farm layout with a medium frequency collection grid interconnecting mutually commutated converters

(Source: [Meier_2009])

10.3.3 Laboratory for Electrical machines and power electronics

Research activities related to multilevel converters. Main circuit analysis and design started two years ago and a 10 kVA experimental prototype has been built and tested. Studies are being conducted on modulation and control [Antonopoulos_2009], [Siemaszko_2010], [Angquist_2010]. Activities related to silicon carbide semiconductors also are pursued [Peftitsis_2010].

11 Visions

11.1 Converter topologies

It appears that the basic approach to VSC-HVDC converters will be some kind of modular multilevel design. The implemented concept may differ between the different manufacturers but the basic principle is similar. It is expected that a lot of research activities will start in order to refine the converter design, its modulation and control system and the important protection methods. It is clear that the modular multilevel converter principle will be applied not only for VSC-HVDC but for a wide range of high-voltage, high-power applications.

VSCs for HVDC have always been rated voltage-wise according to the available voltage for the cables. The multilevel VSCs of M2C or CTL types are scalable due to their modular design. Thus, they can be adapted to any new voltage level that will be developed.

11.2 HVDC cables

The maximum power transfer on AC and HVDC cables is discussed e.g. in [web_transmed_solar]. In order to increase the power transfer capability it is desirable to increase the voltage rather than to increase the current. It can probably be done. Presently transmission using XLPE cables reach about 1200 MW at ±320 kV.

11.3 Semiconductor components

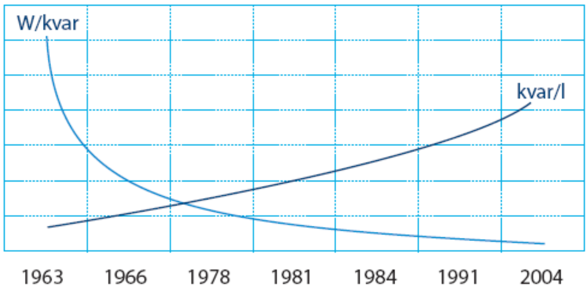
Development of low-loss silicon switching semiconductors can be foreseen due the re-optimization that will follow due to the reduction of switching frequency that is achieved by the use of multilevel converter technology.

Work has been going on for a long time to develop semiconductors using wider bandgap than that in silicon. Such components would present lower on-state losses and higher voltage ratings and they can be operated at elevated temperatures. (Si IGCT and SiC JFET [Peftitsis_2010]).

11.4 Passive components

The phase inductor in the two-level VSC is a significant design issue due to the extremely high voltage derivative applied, when all semiconductor devices in the valve switch simultaneously. It is therefore believed that the arm inductors in the M2C can utilize almost conventional technology.

Capacitors play a big role for size and cost. This fact will be even more pronounced when the multilevel converter technology is used. However, the long-term trend shows a continuous increase of the energy storage capability in capacitors and an associated reduction in cost. This trend is depicted in Figure 11.1.



Development of ABB's power capacitors with respect to losses (W/kvar) and power density (kvar/l)

(Source: ABB Capacitors)

Figure 11.1: General development trend for capacitors

A general description about different capacitor technologies is given in [Sarjeant_1998].

11.5 Switching devices for DC grids

DC switching devices will be necessary if DC grids shall be implemented. It is possible to utilize semiconductor switches for this purpose, but that will cause extra losses. Research in this area is motivated and it is likely that such development is on-going by manufacturers promoting the DC grid concept.

12 Discussion and conclusions

In recent years there has been a great interest for offshore wind power generation and interconnection of wind farms. Several working groups, more or less formal, have been working on the subjects, and a number of suggestions for interconnection of wind farms, mainly in the North Sea, have been presented. Often, the concept of an offshore SuperGrid based on HVDC technology is promoted. However, these thoughts are seldom based on a deeper foundation in specific technologies for power electronic converters or fault-handling strategies. Additionally, it has to be mentioned that these ideas would be immensely costly to realize. The question is what mechanisms for financing of such offshore SuperGrids should be used, and who should finally pay for them. Probably, the initiative must be political involving a great part of the European community. Until recently, the HVDC SuperGrid seemed to be an idea that could not be realized from both a technical and economical perspective. However, the recently introduced M2C technology has the potential to solve all problems related to converter technology, and in conjunction with semiconductor circuit-breaker technology, it is no longer impossible to establish an offshore HVDC SuperGrid from a technical point-of-view.

The dreams of the massive wind power generation in the North Sea and the associated SuperGrid have to be put in a sober perspective in which onshore production must be included. In this context it has to be mentioned that onshore wind power generation is an immense market. Some manufacturers even claim that they concentrate entirely on onshore technology because of the additional problems with offshore technology. Other manufacturers are less categorical in their claims, but reserve new technology for onshore production and more mature technology for offshore generation in order to minimize the risk. Nevertheless, new high-power wind turbines for offshore generation are developed. The cost, and risk, for this is tremendous. A competent guess is that a new wind turbine for offshore generation has a development cost of approximately one billion Euro. With this in mind, it is not surprising that many manufacturers prefer to use established onshore technology in their offshore projects, and if new dedicated technology for offshore is required, great precautions are taken before rushing into new projects.

Before running into conclusions about the development of offshore wind power technology it makes sense to review the considerations made for collection grids, power electronics for interconnection, and DC grid issues.

Currently, there are no other plans than using 10-35 kV AC grids as collection grids in wind farms. The technology used is established 50 Hz technology, even if the frequency may be slightly variable if the interconnection to shore is an HVDC link. Alternative solutions such as DC collection grids or medium frequency collection grids may be very interesting in the future, but many problems are still unsolved, and since offshore technology requires a very high estimated availability, alternative solutions to the established technology will probably have to wait at least a decade.

For wind farms located less than 50 km from a strong connection point on the shore there is no doubt that these will be interconnected with established AC technology also in the future. Even if larger distances are also possible by using inductive compensation, this solution has gained very little interest in the literature.

Long-distance interconnections are almost always considered to be HVDC links. There are a number of examples where classical thyristor-based HVDC links are suggested, often in conjunction with an associated STATCOM on the offshore station. However, no such projects are currently planned. From discussions with experts it is found that there are two main objections against classical HVDC links in this context. First, the intention of installing wind farms is to replace existing conventional fossil-based generation. When conventional generation facilities are disconnected, the strength of the grid is reduced. In this scenario, only technologies that have the potential to support the grid are realistic alternatives. Line-commutated HVDC converters are, therefore, not likely to be used for interconnection of offshore wind farms. Second, the size of the offshore platform of a classical HVDC station is approximately twice the size of a VSC-based counterpart. Finally, it has to be emphasized that the VSC-HVDC system has black-start capability and can operate on very weak networks. The HVDC links interconnecting future wind farms with the grid will, therefore, probably almost always be VSC-based HVDC links.

Until recently, ABB has been the only manufacturer of VSC-HVDC technology. This technology is based on two-level inverters with a very high number of series-connected IGBTs that are switching at the same instant. The brand name of this technology is HVDC Light. In 2007, however, Siemens launched a new VSC-HVDC technology based on cascaded half-bridges. This multilevel technology is called Modular Multilevel Converter (M2C), but the brand name is HVDC PLUS. With this technology it is possible to achieve higher efficiencies than with the two-level technology by ABB. Since then, Alstom Grid has introduced a VSC-HVDC technology based on the same technology as Siemens, but with cascaded full-bridges. The reason for the choice of full-bridges is that it does not intrude on the patents by Siemens. Additionally, Alstom Grid claims that this technology can be used together with classical HVDC. Another important property of the full-bridge technology is that short circuits on the DC side can be handled more effectively. Very recently, ABB has presented a new version of HVDC Light based on cascaded half-bridges like Siemens. However, the variant by ABB makes use of series-connected IGBTs, such that the valves in the half-bridge consist of several series-connected IGBTs. In this way ABB can reduce the complexity of the main circuit, as approximately 5-10 times less cascaded bridges can be used. The press-pack technology by ABB is also able to handle both internal and external short-circuits without additional circuitry.

This leaves the VSC-HVDC market with three brands of basically the same technology. Siemens, on the one hand, is the player with the greatest experience in the M2C technology. ABB, on the other hand, has many years of experience of VSC-HVDC technology both onshore and offshore. Alstom grid is the freshman in this context, even if they have considerable experience from STATCOMs with cascaded full-bridges. With this in mind, it seems that ABB and Siemens are almost equal competitors in this business. Alstom Grid, however, will probably have to wait a few years in order to gain experience enough to be able to compete with ABB and Siemens on equal terms.

Based on the discussion above, there is no doubt that M2C will be the preferred solution for interconnection of wind farms that are distant from a strong connection point on the shore.

A lot of research activities will be conducted to refine the different VSC-HVDC solutions provided by different manufacturers with respect to circuit topology and control and protection.

In all HVDC-interconnection projects discussed so far, only point-to-point interconnections are considered. Ideas of increasing the availability by the use of multiple interconnections are not based on available data regarding availability. This data is unambiguous in the conclusion that the greatest contribution to the un-availability originates from the wind turbines regardless of the type of interconnection.

The greatest drivers for the offshore SuperGrid are, however, removal of bottlenecks in the AC grid and the possibility to redistribute electrical power over the European continent. The potential benefits are enormous, but so are also the costs for realizing it. The M2C technology, especially with full-bridges or the new double-half-bridge topology suggested by Marquardt, seems to be a good choice of power electronic technology realizing the converters for the DC grid. The reason to this is that these topologies have a built-in DC-side short-circuit protection. No DC circuit breakers are, therefore, necessary for protection of the converters. However, when a DC-side short-circuit occurs, and the converters go into the blocking mode, a great part of the grid would have approximately zero voltage. Separation of the faulty part of the grid must be performed as fast as possible. It is not obvious how this should be achieved. One alternative is to have numerous fast-acting DC circuit breakers. This alternative is very costly since it would require an IGBT switch (or similar) which is costly, but not as costly as a VSC. Additionally, each DC circuit breaker would be associated with a conduction loss of the order of 0.1%. Another alternative would be to have only a limited number of such circuit breakers and to let the voltage be approximately zero for the time necessary to operate a fast disconnector. After the disconnection of the faulty part of the grid, the voltage can be brought up again. This solution, however, would probably require short-term energy storage on the AC connection points as the power drop out would cause too serious transients in the AC grid. Energy storage units with power ratings in the GW range are also likely to be very expensive even if only a number of tens of milliseconds are required.

The technical questions related to meshed HVDC SuperGrids have not been investigated thoroughly with respect to specific technologies for power electronic converters or operational or fault-handling strategies. Such activities seem to be on their way now and hopefully the dreams of massive wind power generation in the North Sea can be realized in the future. Due to the needs of an offshore SuperGrid it is not unlikely that the European community decides to invest in such a system. Probably, the first two nodes of such a system would be the offshore hubs in the North Sea. These should be in operation in 2013.

13 References

13.1 Papers and reports

[Allebrod_2008] S. Allebrod, R. Hamerski, R. Marquardt: New Transformer-less, Scalable Modular MultilevelConverters for HVDC-Transmission, Proc. of IEEE Power Electronics Specialists Conferens 2008, PESC '08, June 2008, Rhodes, Greece.

[Angquist_2010] L. Ängquist, A. Antonopoulos, D. Siemaszko, K. Ilves, M. Vasiladiotis, and H.-P. Nee: Inner control of modular multilevel converters – an approach using open-loop estimation of stored energy, International Power Electronics Conference (IPEC), Sapporo, Japan, June 21-24, 2010.

[Antonopoulos_2009] A. Antonopoulos, L. Ängquist, H.-P. Nee: On dynamics and voltage control of the modular multilevel converter, Proc. of EPE 2009, Barcelona, Spain.

[Asplund_2004] G. Asplund: Sustainable energy systems with HVDC transmission, IEEE PES General Meeting 2004, Denver, USA, pages 2299-2303

[Asplund_2010] G. Asplund, B. Jacobsson, B. Berggren, K. Lindén: Continental Overlay HVDC-Grid, Cigré session 2010, paper B4-109-2010

[Bozhko_2007] S. V. Bozhko, R. Blasco-Gimenez, R. Li, J. C. Clare, and G. M. Asher: Control of Offshore DFIG-Based Wind Farm Grid with Line-Commutated HVDC Connection, IEEE TRANSACTIONS ON ENERGY CONVERSION, VOL. 22, NO. 1, MARCH 2007, pp. 71-78.

[Bozhko_2008] S. Bozhko, G. Asher, R. Li, J. Clare, and L. Yao: Large Offshore DFIG-Based Wind Farm With Line-Commutated HVDC Connection to the Main Grid: Engineering Studies, IEEE TRANSACTIONS ON ENERGY CONVERSION, VOL. 23, NO. 1, MARCH 2008, pp. 119-127.

[Carlson_2005] O. Carlson, S. Lundberg: Integration of wind power by DC-power systems, Proc. of IEEE PowerTech 2005, St. Petersburg, Russia, 27-30 June 2005.

[Ehrlich_2008] I. Erlich, C. Feltes, F. Shewarega, and M. Wilch: Interaction of Large Offshore Wind Parks with the Electrical Grid, Proc. of DRPT2008, 6-9 April 2008, Nanjing, China, pp. 2658-2663.

[Foster_2008] S. Foster, L. Xu, B. Fox: Control of an LCC HVDC system for connecting large offshore wind farms with special consideration of grid fault, 2008 IEEE PES General Meeting – Conversion and Delivery of Electrical Energy on the 21st Century

[Jacobson_2010] B. Jacobson, P. Karlsson, G. Asplund, L. Harnefors, T. Jonsson: VSC-HVDC Transmission with Cascaded Two-Level Converters, Cigré session 2010, paper B4-110

[Johnson_EPE2010] A. Johnson: The Development of Technical Requirements for New and Renewable forms of Generation and Offshore Transmission in Great Britain, presentation at the 2010 EPE Wind energy chapter seminar, 15-16 April 2010, Stafford, UK.

[Jovcic_2006] D. Jovcic, J. V. Milanovic: Offshore Wind Farm Based on Variable Frequency Mini-Grids with Multiterminal DC Interconnection, Proc. of IEE ACDC 2006, pp. 215-219.

[Kling_2008] W. L. Kling, R. L. Hendriks, and J. H. den Boon: Advanced Transmission Solutions for Offshore Wind Farms, 2008 IEEE PES General Meeting - Conversion and Delivery of Electrical Energy in the 21st century.

[Kling_2006_Cigre] W. L. Kling, G. Van Der Lee, C. P. J. Jansen, J. F. Groeman. I. O. Doornbos, H. Boomsma, B. A. Wilbrink, F. Wisselink, J. C. Lipman: Development of an electric infrastructure at sea, Cigré session 2006, paper C1-108.

[Koch_Cigre_2008] H.Koch/D.Kunze/S.Pöhler/L.Hofmann/C.Ratke/A.Mueller: Gas insulated lines – reliable power transmission towards new worldwide challenges in hydro and wind power generation, Paper B3-210, Cigre 2008.

[Lesnicar_2003] A. Lesnicar, R. Marquardt: An innovative modular multilevel converter topology suitable for a wide power range, Proc. of 2003 IEEE Bologna PowerTech Conference, June 23-26, Bologna, Italy.

[Li_2007] R. Li, S.V. Bozhko, G.M. Asher, L. Yao, and L. Ran: Offshore grid frequency control design for line-commutated converters high-voltage direct-current link connected wind farms, IET Renew. Power Gener., 2007, 1, (4), pp. 211–219.

[Lu_2005] W. Lu and B. T. Ooi: DC Voltage Limit Compliance in Voltage-Source Converter based Multi-Terminal HVDC, Proc. of IEEE Power Engineering Society General Meeting 2005.

[MacLeod_EPE2010] N. MacLeod, A. Totterdell, G. Nichol, A. Macher, and G. Hentschel : Connection of Off-shore Wind Farms using Voltage Source Converter HVDC Technology, paper at the 2010 EPE Wind energy chapter seminar, 15-16 April 2010, Stafford, UK.

[Marquardt_2010] Modular Multilevel Converter: An universal concept for HVDC-Networks and extended DC-Bus-applications, International Power Electronics Conference (IPEC), Sapporo, Japan, June 21-24, 2010.

[Max_2007] L. Max, T. Thiringer: Control method and snubber selection for a 5 MW wind turbine single active bridge DC/DC converter, Proc. of EPE 2007, Aalborg, 2-5 Sept. 2007.

[Meier_2009] S. Meier: System Aspects and Modulation Strategies of a New HVDC Transmission System for Wind Farms, PhD Thesis, 2009, KTH Royal Institute of Technology, Stockholm, Sweden.

[Meyer_IAS_2006] C. Meyer, M. Höing, A. Peterson, and R. W. De Doncker: Control and Design of DC-Grids for Offshore Wind Farms, Proc. IEEE IAS Annual Meeting 2006, pp. 1148-1154.

[Meyer_2007] C. Meyer, M. Höing, A. Peterson, and R. W. De Doncker: Control and Design of DC-Grids for Offshore Wind Farms, IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 43, NO. 6, NOVEMBER/DECEMBER 2007, pp. 1475-1482.

[Meyer_IAS_2007] C. Meyer, and R. W. De Doncker: Design of a Three-Phase Series Resonant Converter for Offshore DC Grids, Proc. IEEE IAS Annual Meeting 2007, pp. 216-223.

[Monjean_EPE2010] P. Monjean, C. Saudemont, J. Sprooten, B. Robyns, A. Mirzaian, and L. Leclere : Innovative DC connections for offshore wind and tidal current farms, presentation at the 2010 EPE Wind energy chapter seminar, 15-16 April 2010, Stafford, UK.

[Morton_2006] A. B. Morton, S. Cowdroy, J. R. A. Hill, M. Halliday, and G. D. Nicholson: AC or DC? Economics of Grid Connection Design for Offshore Windfarms, Proc. of IEE ACDC 2006, pp. 236-240.

[Mura_2010] F. Mura, C. Meyer, R. W. De Doncker: Stability Analysis of High-Power DC Grids, IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 46, NO. 2, MARCH/APRIL 2010, pp. 584-592.

[Peftitsis_2010] D. Peftitsis, G. Tolstoy, A. Antonopoulos, J.Rabkowski, J.-K. Lim, M. Bakowski, L. Ängquist, H.-P. Nee: High-Power Modular Multilevel Converters with SiC JFETs, IEEE Energy Conversion Congress & Expo ECCE 2010, Atlanta, USA, September 12-16 2010

[Sannino_2006] A. Sannino, H. Breder, and E. Koldby Nielsen: Reliability of Collection Grids for Large Offshore Wind Parks, Proc. of 9th International Conference on Probabilistic Methods Applied to Power Systems, KTH, Stockholm, Sweden, June 11-15, 2006.

[Sarjeant_2008] W.J. Sarjeant, J. Zirnheld, F.W. MacDougall: Capacitors, IEEE transaction on Plasma Science, Vol. 26, No. 5, October 1998, pp. 1368-1392.

[Siemaszko_2010] D. Siemaszko, A. Antonopoulos, K. Ilves, M. Vasiladiotis, L. Ängquist, H.-P. Nee: Evaluation of Control and Modulation Methods for Modular Multilevel Converters, International Power Electronics Conference (IPEC), Sapporo, Japan, June 21-24, 2010.

[Torres_EPE2010] R. E. Torres: A model-based controller for hybrid HVDC using in a Offshore Wind Farms Applications, presentation at the 2010 EPE Wind energy chapter seminar, 15-16 April 2010, Stafford, UK.

[Underbrink_2006] A. Underbrink, J. Hanson, A. Osterholt, and W. Zimmermann: Probabilistic Reliability Calculations for the Grid Connection of an Offshore Wind Farm, Proc. of 9th International Conference on Probabilistic Methods Applied to Power Systems KTH, Stockholm, Sweden, June 11-15, 2006.

[Wang_2010] L. Wang, K.-H Wang, W.-J. Lee, Z. Chen: Power-Flow Control and Stability Enhancement of Four Parallel-Operated Offshore Wind Farms Using a Line-Commutated HVDC Link, IEEE TRANSACTIONS ON POWER DELIVERY, Vol. 25, Issue 2, pp. 1190-1202.

[Westerweller_2010] T. Westerweller, K.Friedrich, U. Armones, A.Orni, D. Parquet, S. Wehn: Trans bay cable – world's first HVDC system using multilevel voltage-sourced converter, Cigré 2010 session, paper B4-101-2010

[Xu_2009] L. Xu, L. Yao, and M. Bazargan: DC Grid Management of a Multi-Terminal HVDC Transmission System for Large Offshore Wind Farms, Proc. of IEEE International Conference on Sustainable Power Generation and Sypply 2009, Supergen 2009.

[Yao_2010] L. Yao, L. Xu, M. Bazargan, R. Critchley: Multi-terminal HVDC grid for network interconnection and renewable energy integration, Cigré 2010 session, paper B4-305-2010

[Zhou_ICEMS_2008] H. Zhou, G. Yang, H. Geng: Grid integration of DFIG-based offshore wind farms with hybrid HVDC connection, Proc. of International Conference on Electrical Machines and Systems 2008, ICEMS 2008, pp. 2579-2584.

13.2 Web sites and reports

[web_ewea_factsheets]:www.ewea.org >Factsheets >Statistics&Targets

[web_ewea_ewi]:www.ewea.org >The European Wind Initiative, Wind power research and development for the next ten years

[web_transmed_solar]:http://www.dlr.de/tt/Portaldata/41/Resources/dokumente/institut/system/projects/TRANS-CSP_Full_Report_Final.pdf: Study commissioned by Federal Ministry for the Environment, Nature Conservation and Nuclear Safety Germany, German Aerospace Center (DLR): Trans-Mediterranean Interconnection for Concentrating Solar Power Final Report

[web_windfacts]:http://www.wind-energy-the-facts.org/en/downloads.html Wind Energy - The Facts (WindFacts)

[web_oceangrid]:http://www.leonard-energy.org/webfm_send/275
TEN-E (Trans-European Networks)

[abb_brochure]: www.abb.com > search for “It’s time to connect”, ABB brochure POW-0038 It’s time to connect with offshore wind supplement

[web_borwin1]:http://www05.abb.com/global/scot/scot221.nsf/veritydisplay/31ea06315cf98474c125768f004ca380/$File/POW-0050%20BorWin%20Rev8%20LR.pdf Grid connection of wind farms - Borwin1

[web_dolwin1]:http://www.abb.co.uk/industries/ap/db0003db004333/8b74a5fe4cc03e44c125777c003f3203.aspx DolWin1

[web_helwin]:http://www.siemens.com/press/pool/de/pressemitteilungen/2010/power_transmission/EPT201007106e.pdf Siemens wins another order from transpower for connecting up offshore wind turbines

[web_borwin2]:http://www.siemens.com/press/pool/de/pressemitteilungen/2010/power_transmission/EPT201006085e.pdf Siemens receives order from transpower to connect offshore wind farms via HVDC link

14 APPENDIX: Interviews with specialists

14.1 Interview with Colin Oates in Stafford 2010-04-14

This is a summary from statements and opinions compiled from notes (made by Lennart Ängquist and Hans-Peter Nee) of an interview with Colin Oates (Alstom Grid) in Stafford (UK) on the 14th of April 2010.

14.1.1 Running projects

The offshore wind power projects with HVDC connection discussed currently are located on the Irish west coast and the Dogger Bank in the North Sea. Although HVDC grids would be possible in both cases, point-to-point connections with VSC-HVDC is the only solution discussed so far. Grid solutions can only be anticipated in a distant future, mainly from a cost perspective but also from a protection perspective.

14.1.2 HVDC with LCC or VSC

No offshore projects with LCC-HVDC links have been built yet. The main argument for using VSC-HVDC links is the compactness. Platforms for VSC-HVDC have only approximately 50 percent of the size of those for LCC-HVDC links.

Areva promotes cascaded full-bridge converters for VSC-HVDC links mainly for IP reasons. Another argument for using cascaded full-bridge converters is the possibility to break short-circuit currents on the DC side. In other words, the converter has a built-in circuit breaker.

VSC-HVDC converters with cascaded bridges can potentially have an efficiency of 99,25% in rectifier operation and 99,24% in inverter operation. Typically, a switching frequency of 150 Hz per device would be used. Increasing the switching frequency to 200 Hz would yield a reduction in efficiency of approximately 0,08%, while the introduction of third harmonic injection could increase the efficiency with 0,13%. Areva has a 17 level 20 MW prototype using sub-modules with the ratings 1,8 kV and 700 A. They are using standard 3,3 kV 1200 A IGBTs.

14.1.3 DC collection grids

DC collection grids for wind farms is an idea which is promoted by E.ON. The main idea is that the transformer weight can be reduced. Areva has made a prototype of a high-frequency transformer for a third party client, that is completely unrelated to power transmission and distribution. This 200 kW prototype had a Metglas core and the frequency was 20 kHz. However, in the GW power range it is best to stick to standard 50 Hz technology. One possible way to realize a DC/DC converter could then be to use cascaded-bridge converters together with standard 50 Hz transformers operating at higher frequencies (but not very high, possibly approximately 1 kHz) than 50 Hz. Such a technology would be possible to realize without major problems.

14.2 Interview with Philip Kjaer in Stafford 2010-04-15 (not confirmed by Philip Kjaer)

This is a summary from statements and opinions compiled from notes (made by Lennart Ängquist and Hans-Peter Nee) of an interview with Philip Kjaer (Vestas) in Stafford (UK) on the 15th of April 2010.

14.2.1 Choice of HVDC technology for interconnection of offshore wind farms

The intention of installing wind farms is to replace existing conventional fossil-based generation. When conventional generation facilities are disconnected, the strength of the grid is reduced. In this scenario, only technologies that have the potential to support the grid are realistic alternatives. Line-commutated HVDC converters are, therefore, not likely to be used for interconnection of offshore wind farms.

14.2.2 DC collection grids

The statement that DC collection grids would increase the efficiency cannot be supported. Standard 50 Hz AC transformers usually have higher efficiencies than corresponding power electronic converters. If the space required for a transformer on an offshore platform is evaluated, it is found that this space is small and that the additional cost for the platform is comparably low.

If a medium voltage DC collection grid would be used, a DC/DC converter with a medium-voltage output has to be placed in the nacelle of a wind turbine. The presence of the high-voltage equipment in the nacelle would cause serious problems to all kinds of maintenance and service in the nacelle. This is a very strong argument against DC collection grids.

Auxiliary power supply: This was not clear to us afterwards.

Onshore wind power is currently a much bigger business than offshore. Special designs for offshore applications are, therefore, avoided and solutions with 50 Hz collection grids are preferred. The development costs of a new wind turbine are of the order of one billion Euro.

14.2.3 Offshore DC transmission grids

In the cases where offshore DC transmission grids are discussed, wind turbines with higher power ratings than those currently available from Vestas are required. The costs for such a development is tremendous. It is, therefore, not likely that offshore DC transmission grids will be established before approximately 2030.

14.3 Interview with Gunnar Asplund in Stockholm 2010-10-05

This is a summary from statements and opinions compiled from notes (made by Lennart Ängquist and Hans-Peter Nee) of an interview with Gunnar Asplund in Stockholm on the 5th of October 2010.

14.3.1 Cable technology

The choice of cable technology for HVDC transmission in offshore applications depends on whether the polarity should be changed and if some part of the cable should be on-shore.

The voltage reversal requirement disqualifies the use of extruded cables due to the risk of "space charges that can arise with extruded insulation and create excessive dielectric stress within the cable in case of a sudden polarity reversal" (Prysmian brochure).

Sub-marine cables always have a moist-shielding lead layer. This is not required for land cables. Therefore, when a substantial portion of the cable is laid on-shore, extruded cables are preferred as they are lighter and cheaper and easier to install.

For sub-marine applications both XLPE and mass-impregnated cables need shielding and armouring. Therefore, the choice is not obvious. However, it is believed that mass-impregnated cables are slightly more expensive due to a more complex design.

The available maximum voltage ratings for the two types differ substantially. For XLPE cables the maximum voltage rating is currently 320 kV (ABB) or 300 kV (Prysmian), whereas the corresponding value is 500 kV for mass-impregnated cables. (Actually, on the ABB and Prysmian web-sites the maximum voltage is said to be 600 kV with a maximum power capability of 2000 MW (ABB) in bipolar operation.) The main reason probably is that the qualification procedure for new cables at new voltage levels is a very costly procedure, which is only performed when required for new upcoming projects. So far XLPE cables have not been used in projects, where the power level has motivated any higher voltage level.

The maximum voltage ratings can, however, be increased in the future. The CIGRE working group about DC grids concluded that the voltage required for intercontinental connections should be at least 800 kV. From discussions with the three major cable manufacturers it is not impossible to increase the voltage rating of XLPE cables up to for instance 800 kV with a maximum power of approximately 3000 MW per cable pair.

The dielectric stress in impregnated cables is higher than that in XLPE cables. It can be noted that the permitted dielectric stress for cables presently is in the range of 15 kV/mm. Reasonable levels are determined from statistical probability considerations (Weibull-distributions). Basically "no" faults are tolerated. To Gunnar's knowledge no spontaneous faults have occurred in HVDC cables, but sometimes mechanical damage has been caused by anchors from vessels. The electrical field strength in cables is far below the withstand capability of the material. Compare the stress in capacitors, which have a fault-tolerant design, where the field strength can reach 200 kV/mm.

The thermal loading is determined by the thermal resistivity in soil rather than the thermal resistivity in the dielectric insulation. The thermal resistivity of both is roughly the same. (A check on the Web indicates that XLPE has thermal resistivity around 7 Km/W, while the value for soil at sea bottom is about 1.2 Km/W.) Therefore the laying distance between cables has substantial impact on the permitted loading.

Experience shows that it is practical to limit the cable ampacity to 1600 A or less. This corresponds to a cable diameter of about 100 mm. If more power is needed it is preferred to increase the voltage or to connect parallel cables. The latter alternative also can contribute to reliability by offering possible redundancy.

The loadability of submarine cables depends on the climate zone, in temperate zones the ambient (water) temperature is about +10°C, in tropical zones +20°C. This means that the power transfer may be reduced say from 800 MW to 700 MW.

Major cable manufacturers:

ABB (Sweden)

Nexans (Norway)

Prysmian (Italy) former Pirelli

14.3.2 Choice of HVDC technology for interconnection of offshore wind farms

Line-commutated HVDC converters are not likely to be used for interconnection of offshore wind farms. The two main reasons are that the offshore platforms are too heavy and large, and that it is very hard to meet the grid codes with this converter technology.

The VSC technology for HVDC seems to converge towards the multilevel concept. Implementation may vary between different manufacturers. Loss typically 1% or even less.

14.3.3 DC collection grids

On-shore wind power is currently a much bigger business than offshore. Special designs for offshore applications are, therefore, avoided and solutions with 50 Hz collection grids are preferred. However, if the offshore market becomes large enough, special solutions for offshore are possible. In this case DC collection grids could be possibly but not necessarily preferred. Permanent magnet based generators combined with step-up transformers and diode rectifiers can be utilized to connect to a medium voltage DC collection grid. The offshore substation in this case would include (resonant) DC/DC converters to adapt to the high-voltage DC transmission voltage.

14.3.4 Actual projects

Siemens Trans Bay ±200 kV in commissioning phase

ABB 400 MW BorWin1 at ±150 kV commissioned, wind turbines presently not ready

ABB 800 MW DolWin at ±320 kV ordered, delivery 2013

Siemens 400 MW BorWin2 at ±150 kV ordered

Siemens 800 MW HelWin at ±300 kV ordered

Scotland transmission system for windfarm island-mainland (Scottish Power)

14.3.5 Offshore DC transmission grids

Large interconnections using HVDC is a hot topic in the international discussion. Gunnar is the chairman of a Cigre working group about this concept. Lately five more working groups have been started on different aspects of this topic.

First, it can be concluded that the basic design principles for a large DC network are similar to those adapted for AC networks. I.e. it is necessary to be able to isolate a failure on any cable segment without de-energizing the whole network. Thus DC circuit breakers must be available. The condition for clearing a fault current in a DC network differs from that in an AC network because no zero-crossings exist. At a short-circuit the current continues to rise until a sufficiently high counter-emf is inserted in series with the line. The rate of increase is so high that it is necessary to break the fault current within 2-4 ms. Mechanical devices therefore do not present an alternative. The only way to achieve such fast switching operations today is to use power electronics. A power electronic switch does not necessarily have to cause high losses. A reasonable assumption is that the losses are of the order of 0.1%. (This may be compared to an extension of the transmission cable.) Such circuit breakers can be made with existing technology.

DC breakers today are used in HVDC installations to break current in the return path in a bipolar station. The principle is that a capacitor is connected in parallel with the breaker. Together with the breaker a resonant circuit is formed by the capacitor and the leakage inductance in the parallel breaker path. When the breaker opens an arc arises causing a negative resistance in the resonant circuit. An oscillating current is created and its amplitude increases until a zero-crossing of the current through the breaker occurs. Then the breaker takes up voltage commutating the current into a parallel MOV varistor, which inserts sufficient counter voltage to extinguish the current. The breaking process takes several tens of ms and the maximum voltage is some tens of kV. This concept is not viable for service in a DC grid.

The problem to selectively detect and localize short-circuits in the network in a few ms, and to determine and communicate adequate switching commands, seems to be very challenging. Problems like breaker-failure backup also must be handled.

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