European Network of
Transmission System Operators
for Electricity

Offshore Transmission Technology

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PREPARED BY THE REGIONAL GROUP NORTH SEA FOR THE NSCOGI (NORTH SEAS COUNTRIES' OFFSHORE GRID INITIATIVE)

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Introduction

The purpose of this document is to give an overview of offshore electricity transmission technologies. In particular this document is concerned with the use of High Voltage Direct Current (HVDC) systems and more specifically with the development of Voltage Source Converter (VSC) technology.

This report has been prepared for the North Seas Countries' Offshore Grid Initiative (NSCOGI) by ENTSO-E's Regional Group North Sea. It has benefited from contributions from the TSO members of that group (from Belgium, Denmark, France, Germany, Luxembourg, the Netherlands, Norway, Rep of Ireland and the UK) and also equipment suppliers and manufacturers through the working group of Adamowitsch.

This report outlines the current state of the main technology groups required for offshore HVDC transmission as well as giving examples of offshore projects (both current and future). Finally some indications of likely unit costs for HV assets are given.

A Note on Sources of Information

In the following sections of this report every effort has been made to use material that can be referenced (academic papers, reports etc). However, some of the information used in producing this report comes from suppliers (in the form of emails and conversations) and is of a commercially sensitive nature for the manufacturers in question. As such certain sources are not disclosed at this point other than to refer to the part of the industry from which it came.

1 Technology

1.1 Technology Introduction

There are three main technology areas that are addressed in this document. These are: subsea cables, High Voltage Direct Current (HVDC) converters and offshore platforms. It is felt that any other technology required for offshore transmission (onshore substations etc.) is already mature and as such is capable of delivering what is required of it. Each of these technologies is explored in detail below. The current capability of each technology and the expected achievable developments that can be made are discussed below.

1.2 HVDC

1.2.1 HVDC Design Overview

HVDC transmission is being increasingly used worldwide for bulk power transmission over long distances, interconnecting asynchronous power systems and for systems where long lengths of cable are required (e.g. offshore). HVDC conversion is the process of taking alternating current (AC) power and converting it to direct current (DC) and vice versa. This has advantages onshore for very long transmission lines, due to reduced losses, but is seeing increased use offshore due to the limitations on the length of traditional AC cables[♣]. AC cables are affected by capacitive charging (see section 1.3.4) which limits the length that can be realistically used to about 70 – 100km. Efforts can be made to compensate for this effect but, even incorporating the increased cost of HVDC (converter stations etc); there is a breakeven point where HVDC transmission becomes the most appropriate option (see Figure 1).

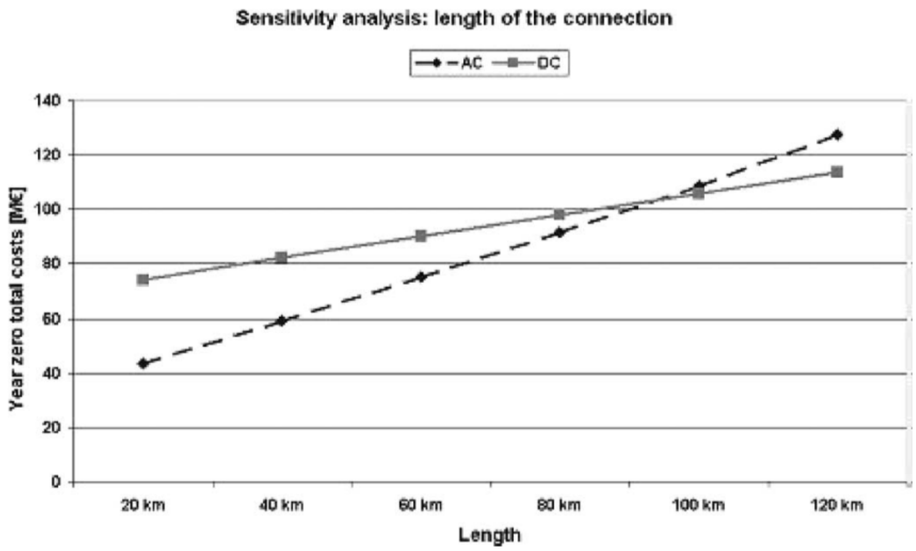

FIGURE 1. RANGE OF CONVENIENCE OF THE ADOPTION OF HVAC OR HVDC CABLE TRANSMISSION SYSTEMS

A HVDC system will consist largely of a converter station at both ends (to create the DC and return to AC) and a DC circuit in between. There are two main types of HVDC technology available on the market. These are current source and voltage source converters.

♣Cables are the only technology currently available for offshore transmission. In the future this may change with the advent of subsea GIL (Gas Insulated Transmission Lines) but it is felt that this technology is not developed enough to be considered in this report.

Current source converters (CSC) are often called by many names including Classic HVDC and Line Commutated Converters (LCC). Voltage Source Converters are usually referred to as VSC.

The basic operation of a HVDC system (regardless of type) consists of feeding AC voltage and current to the rectifier where it is converted from AC to DC. The DC power then flows to the receiving end (via cables or overhead lines) where an inverter converts the power back to AC. This conversion is carried out by semiconductor valves. These semiconductors are largely the governing factor when determining converter ratings (both voltage and current).

On the DC side there are a variety of configurations that can be utilised (eg Monopole, Bipoleetc) to create the optimum connection as can be seen in Figure 2below.

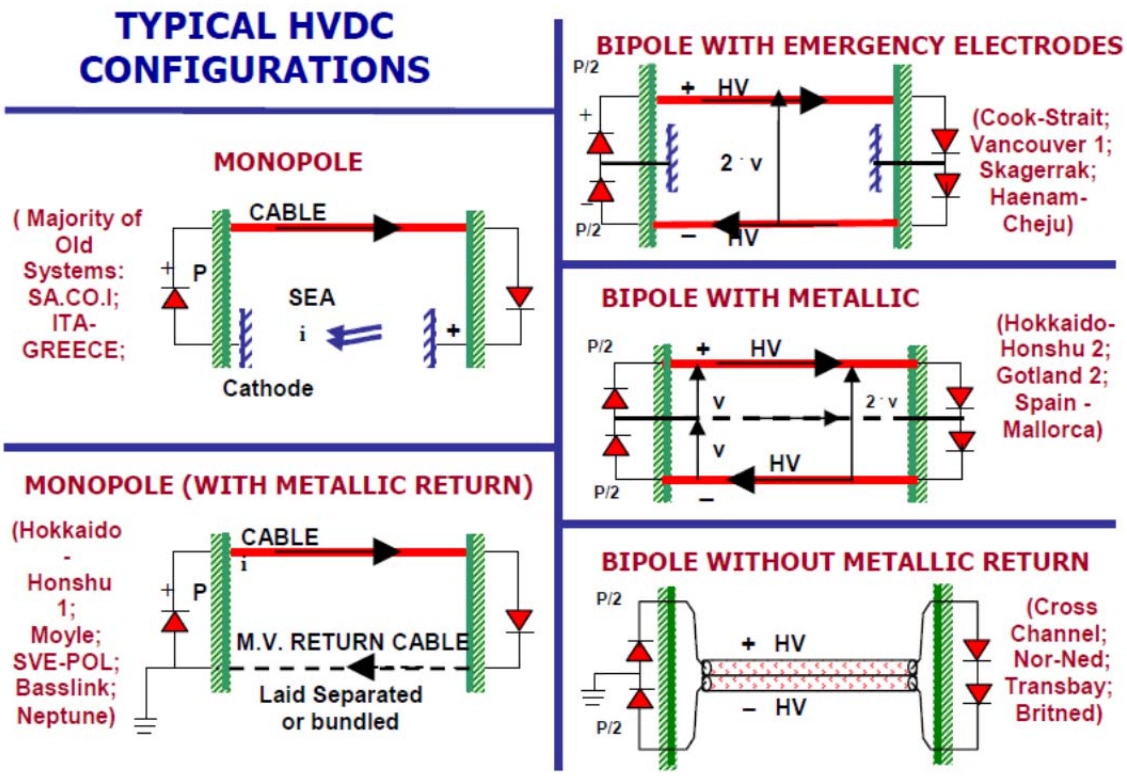

FIGURE 2. EXAMPLES OF TYPICAL LAYOUTS OF HVDC CONNECTIONS(COURTESY OF EUROPACABLE)

1.2.2 Technology Development

There is no theoretical limit to power transfer capability through HVDC converters. Higher voltage and current ratings can be achieved by placing more semiconductor devices in series and in parallel respectively. However practical limits will be reached due to the costs involved, technical difficulties such as maintaining even current sharing across parallel stacks and the physical size of the converter station. There are also system security issues to be considered due to transferring increased amounts of power over reduced circuit numbers.

Developments in performance of the semiconductors themselves (Thyristors and Insulated Gate Bipolar Transistors (IGBTs)) are likely to be incremental at best over the coming years. The main reason for this is that the HVDC industry only makes up a small portion of the market for these devices and as such there is not the incentive for the manufacturers (of semiconductors) to invest in R&D for HVDC purposes. Notwithstanding that even small increases in current and voltage ratings can have an appreciable impact on the power transfer capability of a HVDC system.

1.2.3 Manufacturing Capability

There are currently a limited number of European HVDC system manufacturers operating worldwide. For the purpose of this report it is these manufacturers that will mainly be considered as likely to deliver HVDC solutions in the REGION. These are Siemens, ABB and Alstom Grid (formerly Areva T&D) and all have proven experience delivering CSC HVDC solutions though only Siemens and ABB have so far delivered VSC HVDC systems to the market. Orders for HVDC systems have increased significantly in the last few years and countries such as China intend to construct a significant number of large HVDC systems over the coming years. However these orders will largely be filled by Chinese companies and therefore unlikely to impact on delivery timescales for European projects in the short/medium term. Despite this increase in demand the main limiting factor on timescales delivery of offshore HVDC transmission will most probably remain as the manufacturing of the cable system.

1.2.4 Current Source Converters

Technology Overview

Current Source Converter (CSC) or Line Commutated Converter (LCC) technology is a well established mature technology that was first introduced in 1954. They currently see widespread use around the world in long distance bulk power transmission and interconnecting asynchronous AC systems. A typical CSC HVDC converter station will consist of the following (see Figure 3):

- Current source converter
- Converter transformers
- AC filters and reactive power compensation
- DC smoothing reactors
- DC filters
- Control and Telecommunications

CSC HVDC uses thyristor valves to perform conversion from AC to DC. Thyristors are semi-conducting devices that are capable of conducting current in one direction only. Thyristor valves rely on the external voltage of the AC network to operate as they will only conduct when both triggered by a gate signal and when the anode voltage (of the thyristor) is more positive than the cathode voltage. Converters also consume reactive power in both rectifier and inverter operation. Each valve contains many individual thyristors in order to achieve the current and voltage rating of the converter. A converter station will generally contain at least six valves in a so called six pulse “GraetzBridge”. Modern CSCs will contain 12 valves making up a twelve-pulse converter. The 12 pulse converter is made up of two 6 pulse converters connected in series as seen inFigure 3. However it can be seen from Figure 3 that the bottom converter transformer is a YΔ wound transformer (as opposed to the YY wound transformer above) that produces three phase waveform on the DC side that is 30 electrical degrees out of phase with the rest of the system. This results in a smoother DC output and reduces issues with 6 pulse harmonics on both the AC and DC sides of the converter.

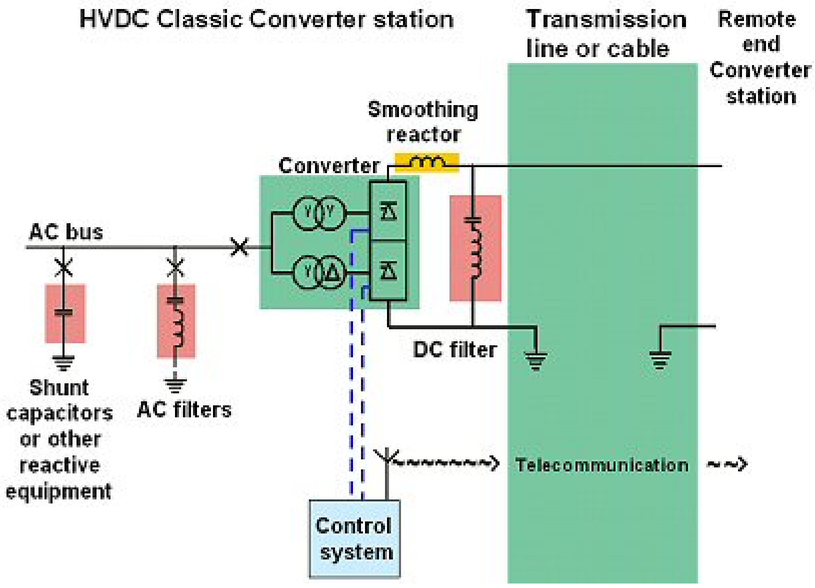

Figure 3. Schematic of a traditional CSC HVDC system (courtesy of ABB)

Converter transformers are specially designed power transformers that interconnect the AC and DC systems. These transformers are subjected to both AC and DC electrical stresses as well as high levels of harmonics and as such must be designed and built to withstand a more extreme electrical operating environment than conventional power transformers.

AC filters, DC filters and DC reactors are all placed in order to reduce harmonics to within agreed specified levels for both the AC and DC waveforms. These harmonics would otherwise affect the quality of power supplied and the total losses.

Reactive power compensation is often added as CSC converters consume reactive power in all operating modes. A more modern design utilises series capacitors to overcome this issue. This is referred to as Capacitor Commutated Conversion (CCC).

CSC HVDC systems require connection to a strong AC network in order to ensure successful commutation and to avoid voltage instability. Commutation is the transfer of current from one phase to another in a synchronised firing sequence of the thyristor valves. The strength of the AC network is measured by the short-circuit ratio (SCR) which is the ratio of the short-circuit power of the AC network to the rated power of the converter. If this value is less than 2-3 the AC system is considered weak. In a weak system STATCOMS, SVCs and synchronous compensators at the point of connection can improve the SCR.

CurrentState of Technology

There are currently many (70-100) CSC HVDC systems worldwide ranging in rated power transfer from less than 100MW to 7200MW. ABB and Siemens have just (in July 2010) commissioned the world's largest Ultra High Voltage Direct Current (UHVDC) system (longest and highest voltage and power transfer). This is a 2000km ±800kV 7200MW system.

Thyristors have developed over the last 60 years to 6 inch 8kV devices with a current rating of 5000A.

As such it can be seen that CSC HVDC is a mature, proven, well understood system that is already operating at ratings far above those ever likely to be required in the REGION.

Future Development and Technology Limitations

The key future development of CSC HVDC technology will be ultra high voltage (> 800kV) and high power. The main limitation of CSC HVDC is its requirement to be connected to a strong AC network at either end. This all but rules out its use for radial connections to offshore windfarms. Also due to the requirement to reverse polarity in order to change the direction of power flow it would be difficult to create a successful CSC multi-terminal system. This also currently precludes the use of XLPE cables for the highest voltage level with CSC due to space charge phenomena in the cable system. This presently mandates the use of mature technology Mass Impregnated cables with CSC HVDC. Nevertheless XLPE CSC technology will be available soon from lower voltage levels.

Technology Risks

When used correctly CSC HVDC has proven time and again to be an economic and technically sound alternative to AC transmission. As such any risks associated with its use are negligible.

1.2.5 Voltage Source Converters

Technology Overview

Voltage Source Converter (VSC) HVDC was first demonstrated in 1997. VSC devices have been used for many years in motor drives where their advantages over CSC devices were widely recognised. VSCs utilise controllable semiconductor switches that do not rely on line voltage for commutation (as CSC HVDC does). VSC HVDC uses Insulated-Gate Bipolar Transistors (IGBTs) which are solid state devices that are self commutating (i.e. can be switched on or off independently of the current flowing through them at the time).

This represents the major difference between VSC and CSC HVDC which uses thyristor valves and a Full Wave Conversion process. VSC based HVDC converter stations use a Pulse Width Modulation (PWM - HVDC Light) technique, or Multi-Level Converter technique (Siemens HVDC PLUS) or a hybrid of the two. Although both of these processes result in higher converter station losses compared with CSC HVDC due to more frequent switching they allow for far more flexible operation.

The main principal of control for VSC based HVDC with PWM is that either the positive or negative voltage potential of the common DC capacitor can be switched to each of the three AC terminals. This creates an approximated waveform at the AC side converter terminals, this must then be filtered using the converter reactor and AC filters to create the desired sinusoid Yet, compared to LCC converters, less filters are required, which leads to a smaller footprint for VSC converters (approx. 50% less).

Due to the fact that they are self commutating, VSC HVDC systems are more suited to the connection of offshore windfarms than CSC as they do not need to be connected to a strong AC network. VSC converters also have a significantly smaller footprint which would make their use offshore easier.

VSC converters also have the ability to control active and reactive power flowing in the converter connection[1]. This is a significant advantage over CSC converters.

A typical VSC converter station will consist of the following:

- AC Transformer
- AC Filters
- Phase reactor
- VSC Converter
- DC Capacitor(s)
- DC reactors

[1]Cigre Working Group B4.39, *Integration of Large Scale Wind Generation using HVDC and Power Electronics*, 2009

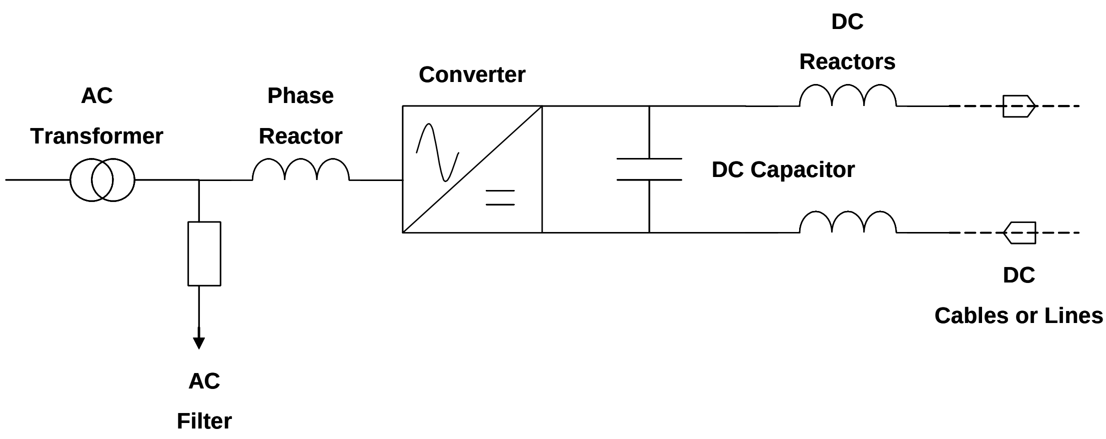

FIGURE 4. DIAGRAM OF VSC HVDC SYSTEM

The DC reactors provide smoothing of the DC waveform on the DC side in order to remove any harmonics and mitigate against possible interference with nearby telephone wires.

The DC capacitor is used to provide a low inductance path for the turned off converter current and to act as an energy store. The DC capacitor also contributes to harmonic filtering of the DC side voltage.

The phase reactors are a key component in the ability of a VSC station to independently control active and reactive power as the fundamental frequency voltage across the reactor defines the power flow between the AC and DC sides. Phase reactors also provide low pass filtering of the AC waveform in order to ensure as close as possible to a perfect sinusoid.Phase reactors also limit any short circuit currents; there is one reactor per phase.

The AC filter, in conjunction with the phase reactors, ensures that the voltage waveform seen at the AC side converter terminal is filtered to a sinusoidal form which can be connected to the AC grid.

Converter Topologies

There are many different configurations of VSC converter available. A two-level solution will generally be the simplest type of VSC converter and thus generally the lowest capital cost solution of the VSC converters. This has been the principle behind ABB's HVDC Light solution.

The PWM technique utilised by a two-level converter does not result in a perfect AC waveform. Hence it must be filtered to create a sinusoid which can be transmitted to the main AC grid.

PWM provides a number of advantages over the full wave conversion method used in conventional CSC HVDC; converters at either end of a link can operate independently of each other, AC voltage can be controlled with a fixed DC voltage and a higher speed of response is obtained. However, due to an increased number of valve switching operations, VSC station losses are higher. The PWM control method can be optimised to eliminate specific harmonics and further increase system stability and power quality.

Building on a two-level converter it is possible to construct a three-level converter. This configuration of converter will likely have a larger footprint and capital cost than a two-level converter but offers advantages such as lower switching frequency (of individual components) and lower voltage rating of IGBT valves (for an equivalent full pole terminal voltage as a two-level converter). Due to the lower switching speed and lower voltage a three-level converter will experience lower losses than an equivalent two-level converter. There are currently several three-level converter systems in operation.

However, recent developments have led to the use of multi-level converters. It is understood that all three European suppliers have either developed or are developing a multi-level VSC converter system.   Multi-level or cascaded converters build up the AC voltage profile in discrete steps rather than using continuous pulsed modulation employed by two and three-level converters. Siemens and ABB are currently the only European manufacturers to have sold multi-level VSC (HVDC PLUS and

HVDC Light). It is understood that Alstom Grid[2] are currently working to bring their own solutions to market.

A multi-level converter process allows a much closer approximation of a sinusoid to be produced at the AC side converter terminals because the magnitude of the output waveform is controllable. This is achieved by the six converter arms acting as a controllable voltage source with many discrete voltage steps. This process produces a waveform at the AC side converter terminal much closer to sinusoid.

A multi-level VSC station provides broadly the same performance as a PWM controlled example, but with some additional advantages; fewer switching operations are required therefore converter station losses are lower (approaching those of CSCs), switching operations take place at a lower voltage, less AC filtering (and in some cases none) is required due to the closer approximation of a sinusoid.

The multi-level design will result in 2n+1 (n=1,2,3….) phase units per converter. There are many different possible topologies possible (HVDC PLUS being one of many possible approaches) and as a result they are not explored in detail here.

Regardless of which control method is used, VSCs provide many technical and operational benefits compared with CSC based HVDC.

Current State of Technology

Since their introduction in 1997 VSC HVDC installations have steadily increased in voltage and current ratings. There are now several VSC links around the world operating in the 400MW range at ±200kV (Eg. Transbay link and BorWin 1). Further to this two 800MW VSC links were announced in 2010 for commissioning in 2013. These are the BorWin 2 connection (Siemens' HVDC PLUS – ±300kV) and the DolWin1 connection (ABB's HVDC Light – ±320kV). In addition to this the INELFE project under construction for the Spain-France interconnection, crossing the Eastern Pyrenees, will consist of 2 bipoles of 1000 MW each (Siemens HVDC PLUS +/- 320 kV) and will be commissioned by 2013. In early 2011 the details regarding the development of the Skagerrak 4 interconnection link were announced. This will be a 500kV 700MW monopole system due for commissioning in 2014. This implies that the capability exists today for a 1400MW VSC HVDC system. Also at the time of writing at least one manufacturer is confident that it can deliver an 1800A IGBT. Combining this with a voltage level of ±500kV would allow an 1800MW VSC HVDC system to be ordered today for commissioning 2014/15.

Future Development and Technology Limitations

It has been indicated to the authors by industry sources that increasing the current rating of IGBTs to 2000A is achievable within the next 3-5 years. The Skagerrak 4 link shows that voltages up to 500kV are currently possible. Therefore it would appear that a ±500kV, 2000MW system could be procured, installed and commissioned by 2017. None of these developments represent a step change in present technology but rather incremental improvements and as such the risk of non delivery is small. This view is backed up by manufacturers and industry groups.

Cigre[3] foresee no technical obstacles to developing and constructing VSC HVDC converters for very high voltage and power (e.g. 600kV, 3000MW). This development is likely to take place using Multi-Level VSC HVDC converters rather than two or three-level designs.

Technology Risks

The main risk to VSC developments will be lack of development in the semiconductor industry. Manufacturers are unlikely to expend time and money developing a solution that they see little or no market for. As such unless they receive a signal from industry that a 2GW VSC HVDC system is required, it is unlikely to be developed.

Comparison of CSC and VSC

CSC HVDC requires a relatively strong synchronous voltage source in order to operate and also must be connected to the network at a point where the three phase symmetrical short circuit capacity is at

[2] Trainer, D. R. et al, *A New Hybrid Voltage-Sourced Converter for HVDC Power Transmission*, 2010, Cigre B4 111

[3] Cigre Working Group B4.37, *VSC Transmission*, 2005

least twice the rating of the converter to ensure commutation within the thyristor valves. This is severely restrictive when considering where an HVDC link can be connected, particularly when considering offshore applications where a STATCOM or synchronous compensator would need to be included on the offshore platform to provide the synchronous voltage source. VSC based installations are self-commutating and can be connected to weak or even passive systems making the technology far more suited to the connection of remote or offshore generation.

CSCs always absorb reactive power whereas active and reactive power can be independently controlled by VSCs; this allows any VSC HVDC links to contribute to the stability and voltage control on the main AC system. This means there is no requirement for additional reactive compensation equipment to meet this demand nor any additional Grid Code requirements for VSCs.

Control methods used for VSCs result in a significant reduction of harmonic production, hence requiring less AC filtering.

VSCs can provide black start capability and can even act as the sole infeed to a passive network.

VSCs have no minimum power limit, and can operate down to zero MWs. CSCs do not have this ability and can only operate down as to approximately 5-10% of rated power.

Multi terminal operation of VSCs is considered easier than with CSC, with manufacturers discussing a ‘plug and play’ system where the network can be easily extended to meet future needs. Despite this the only multiterminal systems in operation today are based on CSC technology. This is likely to change as VSC technology matures.

Present VSC designs experience higher losses than CSC equivalents.

Construction and Installation of Converter Stations

Figure 5 gives an idea of the size and layout of a current source converter station. For a 600MW system the site would be of the order of 200m by 120m. A similar capacity voltage source converter requires less equipment and as such will have a smaller footprint.

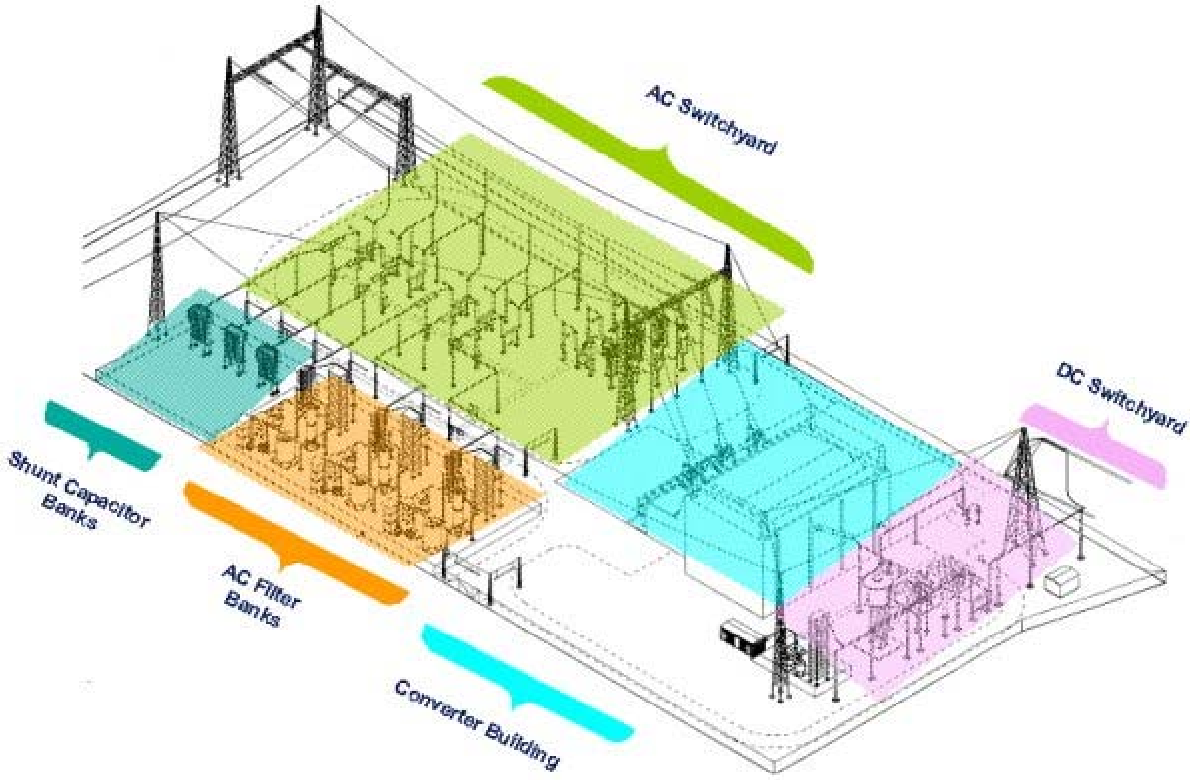

FIGURE 5. TYPICAL LAYOUT OF A CSC HVDC CONVERTER STATION (COURTESY OF ABB)

Offshore transmission requires that converters are placed on offshore platforms such as that in Figure 6. This platform houses a 400MW VSC converter station, weighs 3300t and measures 50 x 33.5 x 22m. Current practice appears to be that the jacket (legs) of the platform and the topside are constructed separately. The jacket is fixed into position on the seabed and the topside is craned into position. For future larger installations this process may no longer be suitable due to the size and weight of the topside. It is envisaged that in this situation the entire platform (topside and jacket) would be constructed together and floated from the shore to its offshore position as one unit.

FIGURE 6. BORWIN ALPHA OFFSHORE CONVERTER STATION (COURTESY OF ABB)

Multi-terminal HVDC

Multi-terminal HVDC refers to HVDC systems with three or more terminals. Multi-terminal HVDC systems have been attempted before using CSC HVDC and there are currently two multi-terminal CSC systems in operation worldwide. A further multi-terminal CSC project (North East – Agra project in India) was awarded in early 2011 with operations planning to commence in 2014-2015. This will be a 800kV system with a converter capacity of 8000MW. Difficulties in CSC multi-terminal systems arise from the fact that in order to change the direction of power flow the polarity of the converter must be switched. This has led to multi-terminal systems where power flow is intended to be in one direction only. This particular constraint is eliminated with the use of VSC HVDC. The development of VSC HVDC systems has raised the possibility of developing a multi-terminal system that behaves more like the AC system that we are used to.

At present a working VSC multi-terminal HVDC systems has not yet been demonstrated, however, technically there are no barriers to the implementation of multi-terminal systems. The authors understand that manufacturers will be in a position to offer a multi-terminal VSC HVDC system within the next few years. To this end several European TOs are currently planning on constructing multiterminal VSC HVDC systems for operation by 2017.

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Standards

Presently, any proposed multi-terminal solution would be supplier specific (i.e. all equipment and control systems would have to be provided by a single supplier). It is not felt that this is an acceptable position as it will have serious consequences on the extendibility and choice available to utility companies. For AC transmission and distribution systems there is a great deal of standardisation of components and voltages among suppliers. This enhances competition and eases the introduction of innovative approaches and techniques. For example there is no requirement for all components of an AC substation (switchgear, transformer, protection equipment etc) to come from the same manufacturer. As such the authors would strongly support the development of standards in the HVDC industry in order to allow a similar level of choice in the future. RG NS members are working towards this by participating in a CENELEC (European Committee for Electro technical Standardization) working group looking at DC Grid standards.

Technology Risk

The main challenge to the successful development of a multi-terminal VSC HVDC system is the lack of standardisation among manufacturers. If it is to remain the case that a single manufacturer's solution will only be compatible with that manufacturers equipment in the future then it will be increasingly difficult for utilities to have the confidence to invest in a multi-terminal solution. Another challenge is that, whilst technically feasible, there are currently no full size demonstration projects in operation to provide confidence to utility companies that multi-terminal systems will perform as designed. There are a multitude of academic papers[♠], manufacturer material and reports from industry groups that attest to the feasibility of multi-terminal VSC HVDC but as yet none has been proven in the "real world". This challenge can be met through detailed design (which will include built in redundancy etc.).

Another challenge to the development of a true multi-terminal system is the lack of DC circuit breakers for transmission voltages. A fault on any of the DC circuits of a multi-terminal system would currently have to be cleared using the AC breakers on the AC side of the converter stations. As such a DC fault would result in the entire multi-terminal system ceasing to operate for the time required to clear the fault and perform any possible reconfiguration of the DC system. This may be manageable with a relatively small number of terminals but as the system size and complexity increases the negative effect will be much larger.

As with the standardisation risk above it will be possible through design of a multi-terminal system to reduce the requirement for DC circuit breakers and the potential impact of a DC fault[4].

[♠] For examples see:

- Tadese, A and Schoore, G, *Control an Protection Philosophy of a mult-iterminal HVDC connection*
- Hendricks, R. L. et al, *Control of a multi-terminal VSC transmission scheme for connecting offshore wind farms*
- Zhou, S et al, *Control of multi-terminal VSC-HVDC transmission system for offshore wind power generation*
- Haileselassie, T. M. et al, *Multi-Terminal VSC-HVDC System for Integration of Offshore Wind Farms and Green Electrification of Platforms in the North Sea*

[4] Jenkins, N et al, Topologies *of multi-terminal HVDC-VSC transmission for large offshore wind farms*, 2010, Electric Power Systems Research

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1.3 Cables

1.3.1 Cable Design

Offshore power transmission requires the use of submarine cable systems. Cables can be constructed to serve both HVDC and HVAC power transmission. The overall structure of different cables is very similar with the main differences arising from choice of materials for the various components. In this report we consider the insulating medium as the main distinguishing factor.

The starting point of any cable is the conductor (or core). The conductor is usually made of stranded copper although aluminium is used in some situations due to its reduced weight and reduced cost. Surrounding the conductor is a layer of insulation. This is the main distinguishing feature between cable types. The insulation can be made from a variety of dielectric materials but this report concerns itself with two main types; Cross Linked Polyethylene (XLPE) and Mass Impregnated Paper[β]. Around the insulation is placed a metal sheath that both prevents moisture ingress as well as providing mechanical strength to the cable. Finally a layer of armouring is placed to increase the cable's tensile strength and allow it to better support its own weight in the water during installation. This is usually a layer of flat or round galvanised steel wires wound helically around the cable, although a double layer can be used in deeper waters or over rocky seabed. This armouring adds to the weight and reduces the flexibility of a subsea cable relative to equivalent land cables. An example of an XLPE submarine cable can be seen in Figure 7.

[β]For high voltage and high power oil filled cables are still available and produced. They can be used for both AC and DC applications

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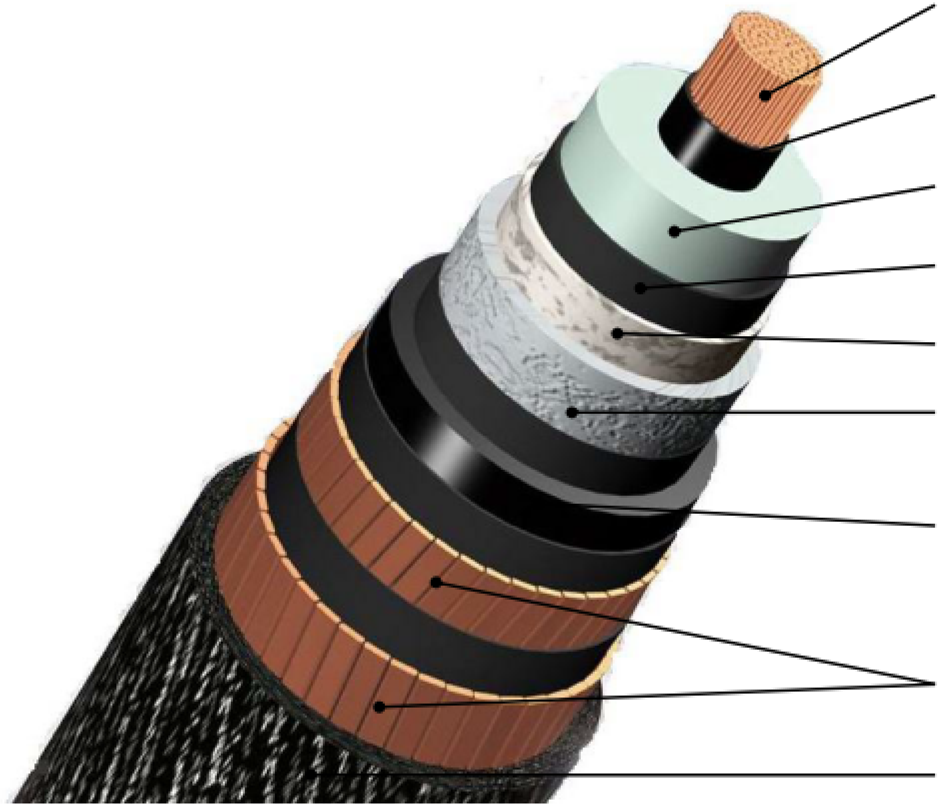

FIGURE 7. EXAMPLE OF SINGLE CORE (XLPE) FOR AC OR DC TECHNOLOGY (COURTESY OF EUROPACABLE)

1.3.2 Technology Development

Several of the designs discussed in this section require development of cable technology beyond that which is presently commercially available or that are not fully tested. Technological solutions have been proposed that are believed to be within reach of the cable design in the near to medium term.

In order to bring these to market however investment in R&D will be required on the part of cable manufacturers. It is unlikely that this investment will materialise without manufacturers having confidence that the market will allow them to recoup their investment.

In order to ensure timely delivery of future cable solutions it is felt that stronger partnership and collaboration among suppliers and customers will be required.

1.3.3 Manufacturing Capability

With ABB, General Cable, Nexans, NKT Cables and Prysmian there are five manufacturers in Europe capable of producing submarine cable systems of the required size and capacity for transmission projects.

Increased capacity to meet the increasing demand will certainly be required, either in the form of extension to existing plants, construction of new manufacturing facilities or the entrance of new players into the European market (most likely from Asia). Additionally, the larger and heavier cables required by the design options outlined in this report will take longer to make and may require the re-tooling of existing lines. Considering the large sums involved, manufacturers will clearly wish to avoid stranded investments (several submarine factories have been closed in the past decade due to a lack of sufficient demand).

Again, stronger relationships between offshore developers and suppliers will assist in ensuring that manufacturing capacity can meet the growing demand for offshore infrastructure. Forward ordering quantities of cable to secure capacity and de-risk investment by manufacturers would benefit this but it is likely to come at a cost premium.

1.3.4 HVAC Submarine Cables

AC cables are widely used and understood in onshore networks, albeit generally over relatively short distances. There is experience in the region and worldwide in their use offshore to connect synchronous networks and remote load centres such as island communities. AC cabling has so far been the preferred technology for connection of offshore wind farms located close to land.

A key limitation of all types of AC cables is their high electrical capacitance which means that for longer lengths of cable the capacitive charging current becomes significant and results in a reduction in their ability to transmit real power. On land this is mitigated against by installing reactive compensation plant in the form of shunt reactors. Generally this is at circuit ends but over longer lengths compensation must be installed mid-route. In the offshore environment it is very expensive to install compensation mid-route as it requires additional offshore platforms and as such economic transmission distances are limited. Indeed, even the installation of shunt reactors at the offshore end off the circuit presents challenges due to the increase in offshore platform weight. As such installing compensation on the shore end only can be considered though this somewhat reduces its effectiveness.

The negative effect of cable charging currents increases with increasing voltage. Therefore as voltage levels are increased to achieve higher cable power capacities, effective transmission distances are reduced (see Figure 8). This has led to the adoption of HVDC connections for long offshore routes such as the Borwin Alpha connection of the Bard 1 offshore wind farm in Germany and the proposed Round 2 and 3 wind farms in UK waters further from shore.

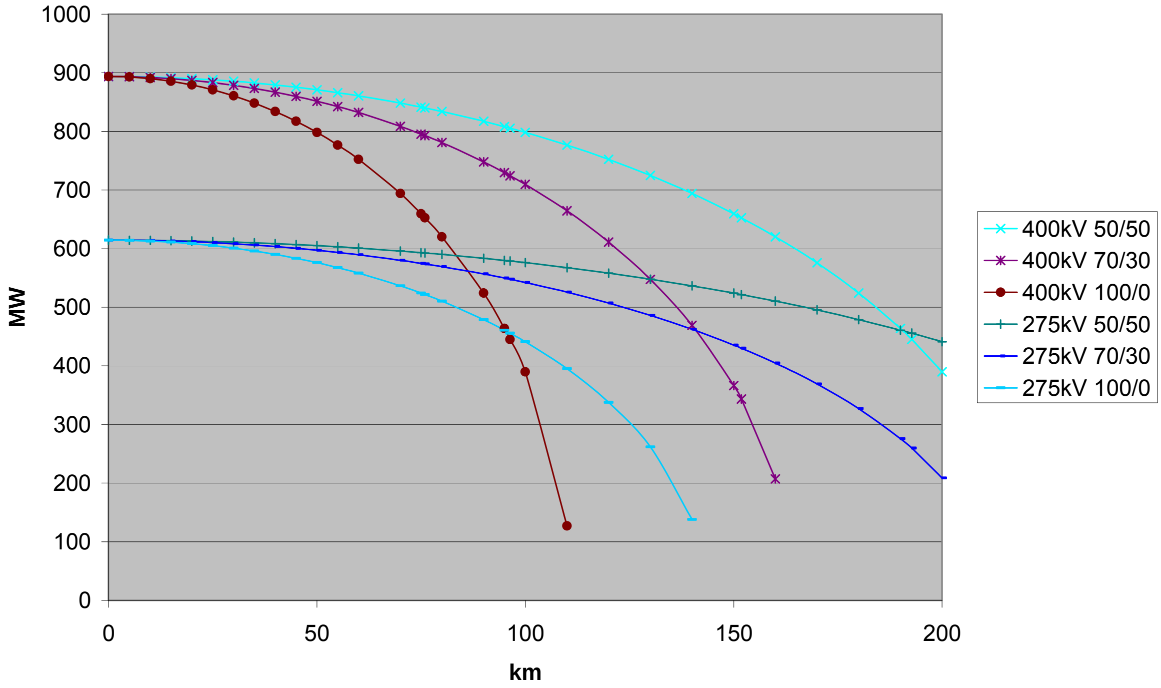

Figure 8. Maximum real power transfer in275 kV and 400 kV AC cables with 100/0, 50/50 and 70/30 reactive compensation split between onshore and offshore (1000 mm^2 copper cross section). This example is for single core cables only and does not take into account other rating limiting factors such as the impact of J tubes and landing points

The electrical insulation used for modern HVAC cables is an extruded polymer (cross linked polyethylene - XLPE) which provides high electrical strength and good mechanical properties at a relatively low weight making it particularly suitable for offshore applications. Conductors can be made from either copper or aluminium.

In the past paper insulated, low pressure oil filled AC cables have been used for some high power subsea applications. However, due to the potential environmental impact in the event of a leak, their relative complexity, the route length limitations imposed by oil feed distances and the emergence of XLPE cables as a competing technology they are used less and less in the European market. As such, oil filled AC cables are not discussed in this document.

1.3.5 HVDC Submarine Cables

HVDC cables have been used since the 1950s for bulk power transmission and energy exchange between asynchronous networks. There are in excess of 20 HVDC submarine cable projects operational worldwide, with many more planned/under construction. The market for HVDC cables is developing rapidly thanks largely to increased demands for renewable generation, leading to demands for increased interconnection between networks and long, high powered offshore connections for wind farms etc.

HVDC cables do not suffer from the charging current limitations of AC cables and transmission distances for HVDC cables are theoretically unlimited. HVDC cables also generally operate at higher voltages than their AC equivalents and as such power densities are higher. HVDC connections should be considered for high power applications or connections located far from shore.

The highest installed HVDC cable rating to date is the 50km Kii Channel crossing in Japan which operates at a DC voltage of ± 500kV and has a conductor cross sectional area of 3000mm^2; each cable is capable of carrying 1400MW (giving a system capacity of 2800MW). As for AC cables, this power rating is achieved using low pressure oil filled cables.

HVDC cables are generally single core, but there are examples (NorNed) of double core HVDC cables being used allowing one bipole circuit to be laid as a single cable. The same can be obtained through the simultaneous laying of two single core cables in the so called ‘bundle configuration’. In fact cables are often bundled, allowing two separate single core cables to be installed in the same trench; however this comes with an accompanying reduction in current rating as a result of mutual heating.

HVDC cables are distinguished mainly by their insulation types. In this report we consider Mass Impregnated Paper and XLPE insulation.

1.3.5.1 Mass Impregnated Paper

Technology Overview

Mass impregnated insulation consists of layers of Kraft paper which are heated, subjected to vacuum and impregnated with high viscosity oil over several weeks. The technology is very mature and has been employed since the 1950s for HVDC applications. A survey conducted by Cigré Working group B1.21 revealed over 15,000km of HVDC Mass Impregnated cable cumulatively installed amongst its respondents prior to 2005.

Mass impregnated paper is not used for HVAC applications due to problems with partial discharge. This is not an issue for HVDC cables due to the lack of rapid polarity reversal.

Current State of Technology

Maximum Installed Rating: *660 MW/Cable (Monopole, 500kV)*

Maximum Planned Rating: *800 MW/Cable (500kV)*

The highest DC voltage currently installed for an Mass Impregnated cable is 500kV for the Neptune project which operates as a 660MW monopole while also allowing (daily) 750 MW for 4 hours overload from previous load of 600 MW.

The highest capacity cable planned is the Fennoskan 2 cable, an extension to the current Fennoskan link between Finland and Sweden capable of transmitting 800MW in a single cable. Several 450kV cables of this type have been installed to date (Baltic Cable, NorNed and the presently commissioning BritNed cable).

Current Mass Impregnated technology would permit transfers of 1000MW/pole on a single cable (i.e. 2000MW per bipole). Significant increases in power beyond this with conventional mass impregnated technology are limited by the cable’s maximum operating voltage and temperature (55^{o}C above which there is a risk of voids in the insulation being created on the cooling cycle as the cable contracts).

Future Development and Technology Limitations

Near Term Achievable Rating: *1500 MW/Cable (3000 MW per Bipole, 600-650kV)*

An emerging technology considers the use of Polypropylene Laminated Papers (PPLP) as the insulation medium which, due to its higher dielectric strength and improved temperature performance (80^{o}C), allows for increased voltages and currents to be realised and thus considerably increased power transfers. Polypropylene Laminated Paper insulation is common in AC, low pressure oil filled applications.

Voltages up to 750kV and 1500MW transfers per cable should be readily achievable with this emerging technology. Voltages of this level may be possible with conventional Mass Impregnated;

however power transfers will be limited relative to Polypropylene Laminated Paper due to the reduced current rating of Mass Impregnated cables.

Significant development has also been made to allow MI cables to be installed and operated in extreme deep waters, with the record of the SAPEI (500kV HVDC, 1000 MW bipole) of up to 1625 m water depth. Other deep water projects are the COMETA (Baleares) 1450 m, and Italy – Greece (1000m).

Technology Risks

Generally, Mass Impregnated cables have been well proven for long and high powered submarine cable projects.

Mass Impregnated Polypropylene Laminated Paper cables, although available on the market and tested, have never been used for HVDC commercial applications. .

There are very few factories capable of manufacturing subsea Mass Impregnated HVDC cables (3 in Europe). With increasing demand in the market, supply chain bottlenecks are likely to develop which could impact project programs, particularly considering the length of time required to manufacture Mass Impregnated cables. Securing factory capacity at the earliest juncture of a cable project of this nature would be prudent. This risk, although applicable to all submarine cable projects, is particularly relevant to Mass Impregnated cables.

1.3.5.2 Cross Linked Polyethylene (XLPE)

Technology Overview

Extruded XLPE insulation is a relatively new entry to the HVDC market, previously dominated by Mass Impregnated cables. The first real utility scale HVDC cable to be installed using extruded XLPE as an insulation medium was the Cross Sound Cable installed in 2002 between Connecticut and Long Island in the northeast USA, operating at ±150kV and capable of transporting 330MW.

XLPE cables have several advantages over Mass Impregnated. In the case of land applications, XLPE cables are lighter which allows longer transportation lengths and therewith longer distances between joints. XLPE land cables are also quicker to manufacture. For long distance submarine cable, factory joints are necessary. Here the distance between joints would be longer for Mass Impregnated cables. Also for submarine XLPE the making of factory joints prolongs manufacturing times., XLPE is generally more mechanically robust and they may operate at higher temperatures (70^o) than Mass Impregnated cables allowing them to carry more current for a given conductor cross section. For this last reason XLPE cables are often used with aluminium conductors to reduce the weight and cost of the cables (although copper conductor is still common for submarine applications). For land applications, pre-moulded joints are available, reducing the time required for cable jointing, making this technology attractive.

XLPE cables cannot presently be used with current source converters (CSC); the reason for this is outlined below.

Current State of Technology

Maximum Installed Rating: *200MW/Cable (400MW/Bipole, ±200kV)*

Maximum Planned Rating: *500MW/Cable (1000MW/Bipole, ±320kV)*

XLPE cables are presently limited to lower voltages and thus lower power levels than Mass Impregnated cables. 150kV was a standard voltage used for many years, although recent projects utilise slightly increased voltages. The Trans-Bay cable uses extruded cables at ±200kV carrying 200MW/cable (400MW total) and the East-West Interconnector from Ireland to the UK due to go into service in 2012 will also operate at ± 200kV and will be capable of transporting 250MW/cable (500MW total). New projects currently under construction (to be commissioned in 2013) are Dolwin 1 and Borwin 2 (both 800MW) at 320 and 300 kV respectively. Sylwin 1 is planned to be 900 MW at 320 kV.

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Currently, the market is able to supply XLPE HVDC cables up to a maximum voltage of 320kV. Using this voltage level, transfers of 1GW per bipole (2 cables with a conductor cross section of 2500 mm^2) are achievable as can be seen by the planned France-Spain link.

Future Development and Technology Limitations

Near Term Achievable Rating: 1000MW/Cable (2000MW/Bipole, 500kV)

There are not perceived to be any barriers to achieving voltages higher than 320kV, should there be a demand for them. 500kV XLPE DC cables could be developed within the next 5 years, allowing power transmission comparable to the Mass Impregnated cables of today, i.e.2000MW per bipole. At 500kV conductor cross sections required to achieve these ratings would be of the order of 1800mm^2 copper. These cables would be of comparable size to the larger XLPE land cables in use today.

XLPE cables suffer from a space charge phenomenon. After being subjected to a constant electric field for a protracted period of time, as in HVDC applications, the insulation becomes polarised and this can lead to breakdown and failure should the polarity of the field be reversed. This renders currently available XLPE cables unsuitable for use in current source HVDC installations where in order to reverse the direction of power flow the polarity must be reversed. Hence XLPE cables can presently only be used in voltage source installations (it should be noted that there are no barriers to pairing traditional Mass Impregnated cables with voltage source converters to achieve higher ratings from a system).

Technology Risks

Although XLPE cables have been in use for many years in the AC market, they are (relatively) new to the HVDC market. As there is no experience in managing these cables to end of life, there is a risk, however slight, that some unknown failure mode may present itself.

Development in XLPE HVDC cables thus far has been rapid. To achieve the ratings proposed a similar rate of increase in voltage levels is required over the next ten years. The development effort in achieving these ratings will not be insignificant and there is a risk that a more fundamental limit preventing further increases in voltage may be reached although this is considered unlikely.

Providing that there are no major unforeseen technical barriers 500kV XLPE cable systems should be expected in the coming years.

1.3.6 Installation of Submarine Cables

The installation of any submarine cable is a challenging operation requiring specific equipment and expertise and should be given careful consideration before commencing any project.

Installation Operation

Cables are installed from a cable laying vessel (CLV) which is either a dedicated vessel or a barge or other vessel modified for the purpose. These vessels are equipped with either a turntable or a so-called ‘basket’ for storing the cable to be installed (baskets are unsuitable for larger submarine cables due to the torsional forces involved when coiling a cable relative to winding onto a turntable). The largest dedicated CLVs on the market currently have turntables capable of storing up to 7000t of cable.

During installation the cable leaves the vessel from the stern over a wheel and follows a catenary line to the seabed. In order to protect it from damage from anchors or fishing gear the cable is buried. This is accomplished either by the use of a ‘plough’ which cuts a trench for the cable to fall into, or by ‘water jetting’ whereby high pressure water jets fluidise a tranche of the seabed which the cable sinks into and is then covered. Ploughing is a faster operation and is generally carried out by the main CLV.

Water jetting is slower and as such is often conducted by a separate vessel following behind to minimise the time that the expensive main CLV is required at sea. Where the seabed makeup does not permit either ploughing or jetting, a cutting machine may be employed to cut a trench for the cable.

When making landfall, either a horizontal directional drilling machine is employed to drill a hole from a point inshore to a point offshore through with the cable is pulled or an open trench is cut over the beach into which the cable is laid.

Installation Risks

The principle risks during cable installation concern damage to the cable, and technical publications exist on this subject. The main technology risks are outlined in brief below.

Choice of a suitable route is essential, and one that avoids difficult seabed topography and geology, as well as existing seabed assets can significantly simplify and de-risk the installation, and avoid reductions in rating from poor cable placement.

If a cable is to be buried in a subsequent operation to laying then for a time the cable will be unprotected on the seafloor. Guard vessels are often employed to minimise the risk of damage during this window.

Dynamic forces on the cable from the motion of the CLV can be severe and difficult to predict (harmonic oscillations along the length of the catenary can be established creating both tensile and compressive forces in turn). Accepted mechanical type tests for submarine cables may not reflect the true nature of the forces accurately. Sophisticated computer modelling tools exist which can assist in the understanding of forces involved.

In addition, as the size and weight of the cables increases (to meet the high power transfers suggested in this report) the stresses involved in laying and beaching the cables increase and the risk of damage and the complexity of the installation operation subsequently increases. This may lead to the requirement for more robust armouring arrangements in shallower water depths, increasing cable weight and reducing flexibility.

Once installed, it is essential to ensure that the cable appears on nautical charts and engagement with other marine environment users (e.g. fisherman; fishing gear is most commonly reported form of damage to submarine cables) at all stages of the project is key.

Installation supply chain challenges

Submarine power cable installation is a highly specialised industry requiring dedicated cable laying vessels manned by a crew with a very specific skill set. Cable laying vessels of the largest size, capable of laying the large export cables required by REGION offshore windfarm connections, are a rare commodity with only two currently operating in the European market and a third under construction. Several smaller vessels with reduced capacities are available and alternatively barges or other vessels may be modified to perform cable laying operations closer to shore and over short distances.

It is understood that several new vessels are under construction although these are unlikely to fully satisfy the demand. Cable laying vessels also find themselves in demand in the oil, gas and telecoms sectors, further increasing competition for their services. The rates on these vessels are highly subject to market forces and as such costs are very volatile and difficult to predict. With increasing demand in the submarine market, cable installation costs are likely to increase sharply. Once again, construction of these vessels requires a high upfront investment and so ways of de-risking this investment should be considered through improved supplier relations and forwardly securing their services.

The skills gap should not be considered insignificant; cable jointers and specialist offshore cable installation knowledge is in short supply. Steps could be taken to close this skill gap through funding of training programs and it is certainly an area in which RG NS would benefit from increasing its own internal knowledge base.

1.3.7 Operation and Maintenance

Subsea power cables have historically been very reliable items of plant with relatively low failure rates and maintenance requirements, although many of the proposed solutions have little to no operational experience worldwide.

When a failure does occur however, it draws on the same resource pool as installation, which as discussed is becoming stretched. As the amount of submarine cable installed increases, more cable failures are inevitable. Additionally, as the capacity of submarine cables increases, both AC and DC, so does the impact of a single cable failure. As such it would be prudent for offshore developers to secure guaranteed access to suitable vessels for cable repair, or purchase dedicated vessels either themselves or through consortia to minimise the repair times and impacts of lost transmission capability.

1.4 Offshore Platforms

Offshore platforms are required to house offshore HVDC converters and associated switchgear and equipment. As converter power ratings increase so does their size and weight. As such this will have an impact on the size and construction of platforms that will house these large converters. Present offshore platforms can weigh up to 4000 tonnes and it is envisaged that this size and weight will increase with larger converters[5]. However there is substantial worldwide knowledge in offshore platform construction from the oil and gas industry where platforms of a weight in excess of 10,000 tonnes are constructed routinely.

Until now offshore substation platforms have largely been bespoke solutions, though a level of standardisation can be seen to be developing among manufacturers. This is expected to continue with the expansion of offshore networks where both manufacturers and the asset owners will be looking for increased standardisation in order to ease construction, maintenance and operation of the assets.

Innovations are expected to occur that should also ease the installation of offshore substations. An example of this is the Siemens "self lifting solution"[6]. Innovations like this reduce the requirement for offshore construction facilities and thus ease the supply chain. This should facilitate a faster rollout of offshore transmission technology.

As such there is no perceived technical barrier to constructing offshore platforms capable of accommodating a 2GW HVDC converter. However, much of the integrated design calls for the installation of two 1GW platforms in order to reduce the risk of stranded assets.

[5] National Grid, *2009 Offshore Development Information Statement – Appendices* [online], 21/12/2009, [Accessed 01/09/2010], Available from:http://www.nationalgrid.com/NR/rdonlyres/62196427-C4E4-483E-A43E-,

[6] Siemens, *The Offshore Way* [online], Available from: http://www.energy.siemens.com/hq/pool/hq/power-transmission/grid-access-solutions/WIPOS/The%20Offshore%20Way_WIPOS.pdf

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1.5 Conclusion

The purpose of this document is to give an overview of offshore electricity transmission technologies. In particular this document is concerned with the use of High Voltage Direct Current (HVDC) systems and more specifically with the development of Voltage Source Converter (VSC) technology.

This document has been prepared by RG NS. However, the analysis is by no means limited to the region but is to serve as a reference document across Europe for the coming years.

Two dimensions are to be distinguished:

1) Convertor station technology
2) HVDC cable technology

1.5.1 Convertor station technology

All three technology groups discussed above will require further development in order to provide an offshore 2GW Multi-terminal VSC HVDC system. However, while this development may present some challenges, it is not felt by manufacturers or technical experts that any technical barrier (such as the multi-terminal issues) cannot be overcome in the immediate future. This document has attempted to show that each of the technologies involved are at various levels of development and implementation.

VSCs have developed strongly over the last 13 years and further development is expected in the coming years. At present the capability of a single VSC is limited to approximately 1400MW. In the near future this is expected to increase to 2000MW via increases in the current rating of the semiconductor components (to 2000A) and increases in voltage rating of converter phase units (to 500-600kV). This leads The authors to the conclusion that proposing the construction of 2GW VSC HVDC links is both economically and technically sound. While a link of this size (using VSC) has not been constructed to date this should not deter companies from pushing the boundaries as the risk is low.

The development of multi-terminal VSC systems comes with slightly more challenges as these are unproven in the field. However a multi-terminal VSC system is technically feasible and any risk could be mitigated through appropriate design considerations and compromises (e.g. in the absence of DC circuit breakers the capacity of the link may need to limited to ensure compliance with infeed loss limits (currently 1320MW in the UK)). Multi-terminal control systems have been intensely studied and as such confidence in their ability to deliver is strong.

1.5.2 HVDC cable technology

HVDC cable systems are a mature technology. Insulating materials mass impregnated and DC XLPE are both applicable for VSC convertor systems depending on their application:

- For applications at voltages higher than 320 kV, for the time being, the preferred insulation material is mass impregnated; relating to submarine connections this is due to the considerable experience obtained in long length manufacturing.
- For applications at voltages not higher than 320 kV, the preferred insulating material for VSC HVDC transmission is XLPE; regarding land applications this is mainly due to the availability of pre-moulded accessories. . It is expected that in the near future this rating will increase to at least 500kV.

Rapid and comprehensive deployment of the European offshore electricity generation and transmission systems will be critical to support Europe meeting it's renewable energy targets. While technical challenges are considerable, manufacturers will be able to deliver the targets, provided they are set against a firm, timely regulatory frameworks to secure the significant investments that will be required.

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2 HVDC Projects

The following section of this document gives an overview of some example offshore HVDC that are currently being planned or constructed in Europe.

2.1 Skagerrak 4

Project Name	**Skagerrak 4**		
Project Start Date	Agreement signed in November 2009	**Commissioning Date**	End of 2014
Voltage	500kV	**Power**	700MW
Connection Length	140km submarine cable and 104km of onshore cable	**Project Cost**	€440m
Terminal Locations	Kristiansand, Norway and Tjele, Denmark		
TOs involved	Energinet.dk (Denmark) and Statnett (Norway)		
Suppliers	ABB – HVDC converters Nexans – Submarine cable and Norwegian land cable Prysmian – Danish land cable		
HVDC Technology	Voltage Source Converter (HVDC Light)	**Cable Technology**	Mass Impregnated Paper
Project Justification	This project will increase the power exchange capability between Norway and Denmark, facilitating the introduction of greater levels of wind energy onto the Danish system by allowing potential intermittency issues to be mitigated by Norwegian hydro power.		
Additional comments and description	Skagerrak 4 will be the 4th point to point connection in the Cross-Skagerrak scheme. Combined with the existing Skagerrak 3 500MW monopole link it will form a 1.2GW HVDC Bipole.		

2.2 BritNed

Project Name	**BritNed**		
Project Start Date	Construction started September 2009	**Commissioning Date**	Early 2011
Voltage	±450kV	**Power**	1000MW
Connection Length	260km	**Project Cost**	€600m
Terminal Locations	Maasvlakte, Netherlands and the Isle of Grain, UK		
TSOs involved	National Grid International Limited (UK) and TenneT (Netherlands)		
Suppliers	Siemens – Converter stations ABB - Cable		
HVDC Technology	Current Source Converter (CSC) HVDC	**Cable Technology**	Mass Impregnated Paper
Project Justification	Several reasons are given for the construction of the BritNed interconnector. These include: • Ensuring security of supply for North West Europe • Ensuring maximum use of renewable generation • Diversifying energy supplies in both the UK and the Netherlands • Promoting price leveling between the UK and the Netherlands		
Additional comments and description	BritNed is a commercial interconnector and therefore funding and operation is separate to both National Grid's and Tennet's regulated activities. In early 2007 connection agreements were signed paving the way for construction activities to commence in the summer of 2007. The link consists of a CSC HVDC bipole configuration connected over 260km using mass impregnated subsea cables.		

	In September of 2009 cable laying commenced at Maasvlakte and in July 2010 this activity was completed. Load flow commissioning started in February 2011 and was ongoing at the time of writing.

2.3 NORD.LINK

Project Name	**NORD.LINK**		
Project Start Date	2014	**Commissioning Date**	2018
Voltage	Unknown	**Power**	1400MW
Connection Length	600km	**Project Cost**	€1,350m
Terminal Locations	Tonstad (Norway) and Diele/Brünsbuttel (Germany)		
TOs involved	Statnett (Norway) and TranspowerStromübertragungs (Germany)		
Suppliers	Unknown at this stage		
HVDC Technology	Unknown at this stage	**Cable Technology**	Unknown at this stage
Project Justification	The subsea cable along with the Norwegian storage capacity will be contributing towards climate protection; be economical, reduce variations in power prices and increase security of power supply.		
Additional comments and description	This project is only proposed at this stage and no investment decision has yet been made. A decision on this is expected in 2013. Discussions are ongoing with respective regulators in Norway and Germany.		

2.4 NorGer

Project Name	**NorGer**		
Project Start Date	2012 (construction start)	**Commissioning Date**	2015
Voltage	±450-500kV	**Power**	1400MW
Connection Length	600km	**Project Cost**	€1,400m (+/-30%)
Terminal Locations	Tonstad (Norway) and Mooriem (Germany)		
TOs involved	The project is being carried out by NorGer KS, a company owned by the Norwegian electricity transmission system operator Statnett (50 per cent), the Norwegian energy companies AgderEnergi AS, Lyse Produksjon AS and the Swiss company Elektrizitäts-GesellschaftLaufenburg (AG), each with a stake of 16.67 per cent		
Suppliers	Unknown at this stage		
HVDC Technology	Unknown at this stage	**Cable Technology**	Unknown at this stage
Project Justification	The intention is to link the Norwegian and German electricity transmission grids. Through the link Germany will obtain access to clean and flexible hydroelectric power, and provide Norway with surplus energy, predominately from wind power. The interconnector will contribute to advanced integration of the European power market, more efficient energy production and increased wind power development.		
Additional comments and description	Norwegian Government prefers regulated TSOs to be owner of the cables		

2.5 INELFE (Interconexión Eléctrica Francia España)

Project Name	**INELFE (Interconexión Eléctrica Francia España)**		
Project Start Date	2011	**Commissioning Date**	2013
Voltage	±320kV	**Power**	2000MW
Connection Length	64.2km	**Project Cost**	€700m
Terminal Locations	Baixas, France and Santa Llogaia, Spain		
TOs involved	RTE (France) and REE (Spain)		
Suppliers	Prysmian – cables Siemens - Converter		
HVDC Technology	Voltage Source Converter (VSC)	**Cable Technology**	Extruded cable
Project Justification	This project will double the interconnection capacity between France and Spain		
Additional comments and description	This project is being constructed as two 1GW bipoles (2GW in total). It consists of converter stations at 64.2km apart in France and Spain. Power will be transferred via underground cables which shall pass through a newly constructed tunnel through the Pyrenees (8.5km in length) and through trenches.		

2.6 Nemo

<table>
<tr><td>Project Name</td><td colspan="3">Nemo</td></tr>
<tr><td>Project Start Date</td><td>Construction to be started in 2014</td><td>Commissioning Date</td><td>2016-2017</td></tr>
<tr><td>Voltage</td><td>Not yet defined, but most likely between 320kV and 500kV</td><td>Power</td><td>+/- 1000MW</td></tr>
<tr><td>Connection Length</td><td>130km</td><td>Project Cost</td><td>€450m</td></tr>
<tr><td>Terminal Locations</td><td colspan="3">Richborough GB
Zeebrugge BE</td></tr>
<tr><td>TSOs involved</td><td colspan="3">National Grid International Limited (UK) and Elia (Belgium)</td></tr>
<tr><td>Suppliers</td><td colspan="3">To be contracted</td></tr>
<tr><td>HVDC Technology</td><td>Voltage Source Converter (VSC) HVDC</td><td>Cable Technology</td><td>To be defined (MI or XLPE)</td></tr>
<tr><td>Project Justification</td><td colspan="3">Several reasons are given for the construction of the Nemo interconnector.

These include:

• Ensuring security of supply for North West Europe
• Ensuring maximum use of renewable generation
• Diversifying energy supplies in both the UK and Belgium
• Promoting price leveling between the UK and Belgium
• Ancillary opportunities (Voltage regulation, black start, …)</td></tr>
<tr><td>Additional comments and description</td><td colspan="3">Major investment decision will be made in 2013.</td></tr>
</table>

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2.7 Alegro

Project Name	**Alegro**		
Project Start Date	Construction to be started in 2016	**Commissioning Date**	2018
Voltage	To be defined	**Power**	500 MW to 1000MW in a first phase
Connection Length	75 km	**Project Cost**	350 M€
Terminal Locations	Lixhe BE VerlautenheideDE		
TOs involved	Elia (Belgium), Amprion (Germany)		
Suppliers	To be contracted		
HVDC Technology	To be defined	**Cable Technology**	To be defined
Project Justification	The project creates value for each of the three pillars of European energy policy. **1. Reinforcing security of electricity supply** **2. Integrating renewable energy sources for sustainability** **3. Contributing to EU market development**		
Additional comments and description	Major decision investment will be made in 2016		

2.8 ROMULO (formerly COMETA)

Project Name	**Romulo (formerly COMETA)**		
Project Start Date	2007	**Commissioning Date**	2011
Voltage	±250kV	**Power**	2 x 200MW
Connection Length	244km	**Project Cost**	400 M€
Terminal Locations	Morvedre (Sagunto, Valencia) and Santa Ponsa (Calviá, Mallorca). Spain.		
TOs involved	REE (Red Eléctrica de España)		
Suppliers	Cable system: Nexans and Prysmian. Converter stations: Siemens.		
HVDC Technology	HVDC "classic": Direct Light Triggered Thyristors.	**Cable Technology**	Mass Impregnated
Project Justification	Improvement of security of supply in Balearic system, while reducing cost of supplied energy.		
Additional comments and description			

3 Costing Information

Where technology/installation costs are identified, these are indicative only and have been compiled using a number of sources. For more readily available items, existing and/or historical pricing has been used as the primary source. For items not directly purchased by The authors in the past, costs have been obtained through a dialogue with key suppliers. In some instances, representative projects were the only available data points to determine cost.

It should be noted that costs for some equipment and service categories can be impacted significantly by market conditions, most notably submarine cables and marine vessel chart rates.

The costs in the following section have been sourced from the converted from British Pounds to Euros using an exchange rate of 1 pound to 1.15 Euros[7].

3.1 HVDC Converters

3.1.1 Voltage Source Converters

All costs are given in millions of Euros.

Specifications	Unit Cost
500 MW 300 kV	75 – 92
850 MW 320 kV	98 – 105
1250 MW 500 kV	121 – 150
2000 MW 500 kV	144 – 196

Notes:

1. Pricing including AC switchyard costs and excludes platform costs.
2. Pricing is based on discussion with VSC suppliers and on representative sample projects that have been recently completed and/or quoted.
3. It is to be noted that the larger ratings are projections based upon discussions with the main equipment suppliers but represent "next generation" technologies and are hence indicative rather than definitive.

3.1.2 Current Source Converters

All costs are given in millions of Euros.

Specifications	Unit Cost
1000 MW 400 kV	81 – 104

[7] Costs have been sourced from the 2011 Offshore Development Information Statement produced by National Grid which can be found here: http://www.nationalgrid.com/uk/Electricity/ODIS/CurrentStatement/

2000 MW 500 kV	150 – 184
3000 MW 600 kV	196 – 230

Notes:

1. Parametrically estimated from known recent CSC contracts.

3.2 HV Plant

3.2.1 Transformers

All costs are given in millions of Euros.

Specifications	Supplied Cost
90 MVA 132/11/11 kV	0.8 – 1.5
180 MVA 132/33/33 or 132/11/11 kV	1.15 – 2.07
240 MVA 132/33/33 kV	1.4 – 2.3
120 MVA 275/33 kV	1.4 – 1.84
240 MVA 275/132 kV	1.73 – 2.3
240 MVA 400/132 kV	2.07 – 2.53

Notes:

1. Prices are for transformers supplied to THE REGION and assembled. Prices do not include civil works or associated bay works. Prices assume customer has some degree of purchasing leverage and sources on global markets.
2. Associated civil costs can approximately double the total installed bay cost but are likely to be an element of a main works contractor costs.
3. Material cost given assumes current pricing for the various relevant commodities; cost subject to fluctuation based on changes to commodity indices.

3.2.2 HVAC GIS Switchgear

All costs are given in millions of Euros.

Specifications	Total Substation

	Cost per bay
132 kV	1.26 – 1.61
275 kV	3.34 – 3.68
400 kV	4.37 – 4.72

Notes:

1. Cost figures are for installed substation complete, including civil works.

3.2.3 Shunt Reactors

All costs are given in millions of Euros.

Specifications	Supplied Cost
60 MVAr/13 kV	0.58 – 0.92
100 MVAr/275 kV	2.76 – 2.99
200 MVAr/400 kV	2.53 – 2.76

Notes:

1. Prices are based upon a unit, delivered and assembled but exclude all civil and structural works associated.
2. Associated civil costs can approximately double the total installed bay cost but are likely to be an element of a main works contractor costs.

3.2.4 HVAC Shunt Capacitor Banks

All costs are given in millions of Euros.

MVAr of capacitive reactive compensation	Installed Cost
100	3.45 – 5.75
200	4.6 – 8.05

Notes:

1. Costs are for a total installed cost, including associated site works.

3.2.5 Static VAR Compensators

All costs are given in millions of Euros.

MVAr of reactive compensation	Installed Cost
100	3.45 – 5.75
200	11.5 – 17.25

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Notes:

1. Costs here are for a total installed cost, including associated site works.

3.2.6 STATCOMs

All costs are given in millions of Euros.

MVAr of reactive compensation	Installed Cost
50	3.45 – 5.75
100	5.75 – 11.5
200	11.5 – 23

Notes:

1. Costs here are for a total installed cost, including associated site works.

3.3 Cable Systems

3.3.1 HVDC Extruded Subsea Cable

All costs are given in Euros per metre of cable supplied (but not installed).

Cross-sectional Area (mm^2)	150 kV	320 kV
1200	230 – 460	345 – 518
1500	288 – 460	345 – 518
1800	345 – 518	345 – 575
2000	345 – 575	403 – 660

Notes:

1. Price given is for total supplied cable cost including metal core, although commodity costs are clearly subject to significant fluctuations and comprise some 30%-40% of total cost.
2. Prices are per metre of cable, supplied. Note that the cost per route-km will depend upon the number of poles and the number of cables per pole.
3. Figures should be taken as indicative pricing. Pricing for this category of items is highly volatile depending upon market supply and demand. Figures presented are based upon a moderate level of competitive intensity but can vary significant depending upon how busy factories become.
4. Prices based upon input from manufacturers tempered with knowledge from recent known contracts.

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3.3.2 Mass Impregnated Insulated Subsea Cable

All costs are given in Euros per metre of cable supplied (but not installed).

Cross-sectional Area (mm^2)	400 kV	500 kV
1500	403 – 660	460 – 660
1800	460 – 660	460 – 690
2000	460 – 690	460 – 748
2500	575 – 805	575 – 863

Notes:

1. Price given is for total supplied cable cost including metal core, although commodity costs are clearly subject to significant fluctuations and comprise some 30%-40% of total cost.
2. Prices are per metre of cable, supplied. Note that the cost per route-km will depend upon the number of poles and the number of cables per pole.
3. Figures should be taken as indicative pricing. Pricing for this category of items is highly volatile depending upon market supply and demand. Figures presented are based upon a moderate level of competitive intensity, but can vary significant depending upon how busy factories become.
4. Prices based upon input from manufacturers tempered with knowledge from recent known contracts.

3.3.3 HVAC 3 Core Subsea Cable

All costs are given in Euros per metre of cable supplied (but not installed).

MVA Rating	Voltage	Supplied Cost
200	132 kV	518 – 805
300	220 kV	575 – 863
400	245 kV	748 – 1150

Notes:

1. Price given is for total supplied cable cost including metal core, although commodity costs are clearly subject to significant fluctuations and comprise some 30%-40% of total cost.
2. Figures should be taken as indicative pricing. Pricing for this category of items is highly volatile depending upon market supply and demand. Figures presented are based upon a moderate level of competitive intensity but can vary significant depending upon how busy factories become.
3. Prices based upon input from manufacturers tempered with knowledge from recent known contracts.

3.4 Connecting to AC Land Systems

3.4.1 HVAC Overhead Lines

HVAC land transmission lines in Europe are and will be largely comprised of overhead lines.

Costs of HVAC overhead lines will average as follows (given in millions of Euros).

Description	Total Cost
Cost per route km 400 kV, double circuit	1.73 – 2.19
Cost per route km 132 kV, double circuit	0.81 – 1.04
Cost per route km 132 kV, single circuit	0.58 – 0.69

Notes:

1. Prices include all installation works.

In sensitive areas, HVAC partial undergrounding may complement the overhead lines. Based on the ENTSO-E / Europacable Joint Paper on the "Feasibility and Technical Aspects of Partial Undergrounding of Extra High Voltage Power Transmission Lines", the investment cost for underground cable solutions is typically 5 to 10 times higher than overhead line costs for the section in which partial undergrounding is applied[8].

Note: It may be beneficial to consider a prolongation of the DC underground cable coming from the shore to a point further in land before linking to the AC system.

[8] ENTSO-E and Europacaple, *Feasibility and technical aspects of partial undergrounding of extra high voltage power transmission lines* [online],2010, Available from:
http://ec.europa.eu/energy/infrastructure/studies/doc/2010_high_voltage_power_transmission_lines.pdf

3.5 Offshore Platforms

3.5.1 AC Platforms

Case Study 1: 132/33 kV 300 MW HVAC (25 x 20 x 18 metres weighing 2000 tonnes)

All costs are given in millions of Euros.

Water Depth	**20-30 metres**	**30-40 metres**	**40-60 metres**
Topside	21 – 26	21 – 26	21 – 26
Jacket	5.75 – 9.2	6.9 – 11.5	9.2 – 13.8
Install	5.75 – 9.2	6.9 – 9.2	6.9 – 11.5
Self Installing	33 – 38	35 – 39	36 – 40

Case Study 2: 220/33 kV 500 MW HVAC (40 x 30 x 18 metres weighing 2500 tonnes)

All costs are given in millions of Euros.

Water Depth	**30-40 metres**	**40-60 metres**
Topside	27.5 – 32	27.5 – 32
Jacket	9.2 – 11.5	11.5 - 15
Install	5.75 – 9.2	6.9 – 11.5
Self Installing	42.5 – 46	43.7 – 49.5

3.5.2 DC Platforms

Case Study 1: 400 MW Voltage Source ±300 kV; Platform (3500 tonnes)

All costs are given in millions of Euros.

Water Depth	**30-50 metres**
Topside	32 – 38
Jacket	9.2 – 12.65
Install	18.4 – 23
Self Installing	69 – 80.5

Case Study 2: 800 MW Voltage Source ±300 kV or 1000 MW Voltage Source ±500 kV; Platform (8000 tonnes)

All costs are given in millions of Euros.

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Water Depth	30-50 metres
Topside	69 – 92
Jacket	23 – 29
Install	31 – 36
Self Installing	138 – 167

Notes:

1. Figures based on traditional designs, not self-installing topsides.

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3.6 Subsea Cable Installation

Cable installation costs vary greatly; prices range from 230 – 977.5Euros/route-metre. The cost variances are a result of the following:

- The prevailing market conditions for specialist vessels and hence the market rates, which are markedly volatile.

  Different combinations of vessels can also be used depending upon the cable type, approach and vessel availability.

- The location of the cable installation relative to the supplier's manufacturing facilities and hence transfer times involved.

  Cable laying is done in campaigns, governed by the amount of cable that can be carried on the vessel at one time. Either the cable laying vessel must return to the factory to reload or must be supported by barges that reload it on location.

- The type of cable and its burial depth and hence whether ploughing, jetting or trenching is the preferred option.

  The ground conditions, chosen depth and cable type will govern the installation method and will impact the rate of cable installation. Burial depths can significantly impact the speed of laying as can the sea bed conditions.

- The number of cables and the configuration (whether bundled or discretely laid).

  Cables can be bundled and laid in a single trench or can be placed in adjacent trenches, depending upon the design configuration.

- The rating of the cable and it size, and hence the number of installation campaigns, also being influenced by the size of cable laying vessel available.

  Vessels tend to have weight limit on their turntables and hence cables with higher rating will have shorter lengths, with more campaigns, and more joints.

- The location risks and preferred approach to cable laying and leaving cable laid on the sea bed. Different approach can be adopted, with different cost and risk profiles. Cable laying and installation operations can be separated, with different vessels employed for different tasks.

- There are additional, route-specific costs such as the cost of landing cables at different locations (e.g. drilling under seas defences) and the number of crossings that occur, where various forms of cable protection need to be deployed (rock dumping, mattresses).

Inevitable, such costs should be estimated on a project basis.

Cost Summary: Illustrative costs for different cable configurations.

All costs are given in thousands of Euros.

Installation Type	Total Cost (per km)
Single cable, single trench	345-805 excluding materials, ancillary vessels and surveys
Twin cable, single trench	575-1035 excluding materials, ancillary vessels and surveys
2 single cables; 2 trenches, 10M apart	690-1380 excluding materials, ancillary vessels and surveys

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4 Document Change Log

Version	Date	Comment
1	24/03/2011	First release for review
2	12/04/2011	Document Revised based on comments from Energinet.dk, STRI and ABB
4	15/06/2011	Document revised based on comments from Europacable
5	23/06/2011	Document revised based on comments from Kjartan Hauglum (Statnett)
6	24/06/2011	Document revised based on comments from Frederic Dunon (Elia)
7	30/06/2011	Document revised based on comments from Olivier Despouys (RTE)
8	20/07/2011	Document revised based on comments from Nigel Platt (Siemens)
9	05/10/2011	Section 3 costs updated following publication of the 2011 Offshore Development Information Statement
10	26/10/2011	Update following comments from Gerald Kaendler (Amprion), Claire Fourment (RTE) and Luis Imaz Monforte (REE)
10	16/10/2012	Update on the maximum voltage level (750 kV) for Mass Impregnated cable

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