An Introduction to High Voltage Direct Current (HVDC) Subsea Cables Systems

Brussels, 16 July 2012

An Introduction to High Voltage Direct Current (HVDC) Subsea Cables Systems

Table of content

1. Introduction

High Voltage Direct Current (HVDC) subsea cables systems are a key technology for the development of the future European electric power transmission networks. They serve two functions:

- to interconnect countries or islands separated by sea; and
- to connect remote offshore platforms to main transmission grids.

With this paper, Europacable seeks to provide an authoritative source of information about HVDC subsea cable system technology.

Application of HVDC Transmission Technology

Generally speaking, HVDC transmission technology has been applied since the beginning of electricity transmission around 1880s. In the early 1950s, HVDC transmission technology was then developed to fulfill specific requirements for subsea interconnection based on the availability mercury arc valves used for electric AC/DC converters. In principle, High Voltage Direct Current (HVDC) transmission lines are applied when there is a need to transport high electrical power over long distances and/or in a controlled manner.

Since then, HVDC transmission technology is applied in submarine application either for connecting offshore platforms and windmill fields to land or for transmitting electricity over long distances through the sea where overhead lines cannot be used. Another key application is the connection of islands to the mainland.

HVDC transmission is the only solution available for the transfer of high power across long subsea distances. Furthermore, HVDC is a proven technology for transmission projects that interconnect asynchronous networks.

Today, HVDC subsea transmission technology is largely applied in single point-to-point connections. The system approach gives the effective rating. Current maximum HVDC power under planning is up to +/- 600 kV and 2.200 MW per bipole as a system.

Looking into the future, meshed HVDC subsea systems will become available. Their creation is today still limited as circuit breakers are only beginning to be introduced. Circuit breakers, so called switchgear, secure the operation of the meshed HVDC system.

History of HVDC Subsea Cables Systems

- **1880**: Started what is known the "war of current" between George Westinghouse (supporting AC) and Thomas Edison (supporting DC) . DC survived for 10 years, with the first +/- 2 kV DC underground cable being installed from Miesbach to Munich, Germany, covering 57 km in 1882. However, the use of transformers in the late 1880's led to AC becoming the network concept in the world.
- **1950's:** Introduction of valves makes LCC converters available and submarine paper cables come into operation at voltages < +/- 300 kV – many of which are still working today, for example
  - Gotland 1 Connection: 1953, 100kV monopole, 20 MW, 100 km
  - Vancouver Island Connector: 1969, +/- 300 kV, 156 MW, 3 cables 27 km each
  - SACOI linking Sardinia, Corsica and Italy:1956, +/- 200 kV 100 MW, 2 cables 118 km each
  - Skagerrak 1 linking Norway to Denmark: 1976, +/- 263 kV, 250 MW, 2 cables 125 km each
- **1970's:** Introduction of electronic switch "thyristors" makes DC paper cables technology with voltages up to +/- 500 kV widely available
- **1999:** First XLPE DC cable in Gotland, Sweden, VSC connection of an offshore windfarm +/- 80 kV, 50 MW, 2 cables 70 km each
- **2004**: Troll 1 and 2, Norwegian Platforms, VSC connection of an oil platform +/-60 kV, 84 MW, 4 cables 70 km each
- **Today**, over 5.000 km of HVDC subsea cables are in operation around the world.

2. HVDC Subsea Cable Technology

High Voltage Direct Current (HVDC) subsea cables have been in commercial use since the 1950's. Today, two HVDC cable technologies are available[1]:

Paper lapped cables:

This type of cable is currently the most used. It has been in service for more than 40 years, has proven highly reliable and can be provided by European manufacturers at voltages up to +/- 600 kV and 1800 A DC which corresponds to a maximum pole rating of 1100 MW and bipole rating of 2200 MW. Conductor sizes are typically up to 2500 mm^2.

Polymeric cables, e.g. XLPE:

Polymeric cables are mainly used in Voltage Source Converters applications that allow the power flow to reverse without reversing the polarity.To date, this technology has been applied at voltages up to +/- 200 kV (in service with a power capacity of 500 MW). There are projects at an advanced construction stage at the voltage of +/- 320 kV and 800 MW power and ongoing projects at 1000 MW per bipole, and it is expected to increase the voltage and power in the near future.

[1] Self-contained fluid filled (SCFF) cables have also been used for very high voltage and short connections due to the hydraulic limitations since the 1930s.

2.1 Interconnections with HVDC subsea cables

HVDC subsea cable systems serve to interconnect countries or islands separated from the mainland by the sea.

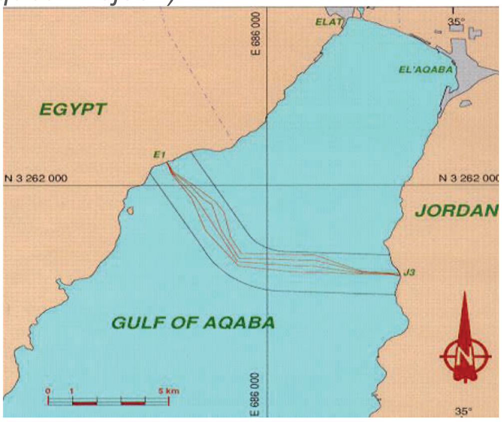
It needs to be stressed that each HVDC subsea cable system is tailor made for each individual project in order to correspond to the specific project requirements. The examples hereunder illustrate the different categories of HVDC subsea cable technology options available today.

2.1.1 Low pressure oil filled cables as HVDC subsea cables

Paper insulated oil filled cables are highly suitable for HVDC transmission for distances up to approximately 50 km due to hydraulic circuit limitations. The insulation system in these cables is constantly under oil pressure to avoid the formation of cavities when the cables are cooled down and the oil contracts. Oil filled cable systems have been qualified for use in AC and DC operations. Examples using low pressure oil filled cables are the interconnections between Saudi Arabia - Egypt ("Aqaba Project") and the Spain-Morocco project:

- *The Saudi Arabia – Egypt Interconnection ("Aqaba Project")*

  Four oil filled cables were installed across the Gulf of Aqaba linking Saudi Arabia to Egypt during May to June 1997. The cables were installed to a record water depth of 850m. The cables were qualified for 420 kV as AC cables and for +/- 400 kV voltage level in DC operation. Route length of the project was 13 km.

  The cables are operated as AC cables, but the power transfer capacity of the 4 cables can be increased from 550 MW to 2000 MW by switching to DC operation[2].

- *The Spain - Morocco Interconnection*

  
  Spain Morocco cable

  The first interconnection between Spain and Morocco was installed in 1997, deploying low pressure oil filled HVDC cables over a total route length of 28,5 km of which 27 km under sea. This interconnection initially consisted of 4 submarine cables installed at a maximum water depth of 615m. A contract for 3 additional cables was awarded in 2003. The cables were qualified for operation at 420 kV AC and for +/- 450 kV DC. The power transmission in AC operation is 700 MW and can be upgraded to 2000 MW by switching to DC operation.[3]

2 More references can be found in: G. Balog, T. Clasen, E. Kaldhussaeter, K. Stenseth, "The Gulf of Aqaba Submarine Cable Crossing", CIGRE session 1998, paper 21-302
3 More references can be found in: R. Granadino et al., "Challenges of the Second Submarine Interconnection between Spain and Morocco", Jicable 2007

2.1.2 Mass-impregnated HVDC subsea cables

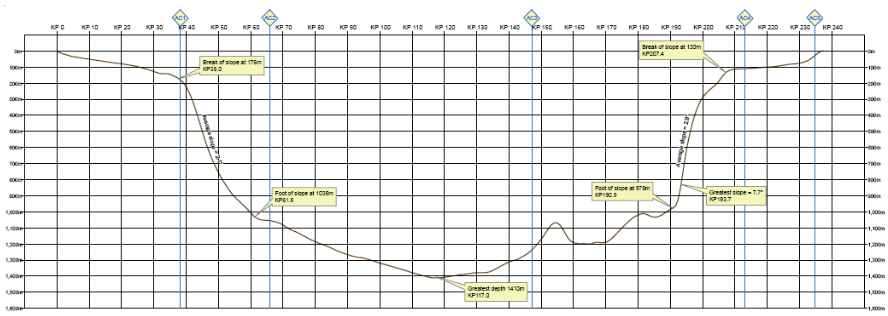
Mass-impregnated subsea HVDC cables do not need oil feeding from the ends and have as such no limitation in length. Mass-impregnated cables are composed by a very high viscosity impregnating compound which does not cause any leakage in case of cable damage or failure. Compared to oil filled cables, the compact design is also an advantage for deep water applications.

An example using mass-impregnated subsea HVDC cables is the interconnection between Spain – Mallorca ("Cometa Project"):

- *The Spain – Mallorca Interconnection ("Cometa Project")*

  In 2011, a 400 MW HVDC link has been constructed and put in service between the Spanish mainland and the island of Mallorca. The link is operated as a bipole with two HVDC mass-impregnated cables at +/- 250 kV voltage level and with a separate XLPE insulated metallic return conductor.

  The main challenge in this project is the large depth of the route. The figure below shows the route profile indicating that approximately 50% is at a water depth below 1000m including several steep slopes with a maximum depth of 1485m.

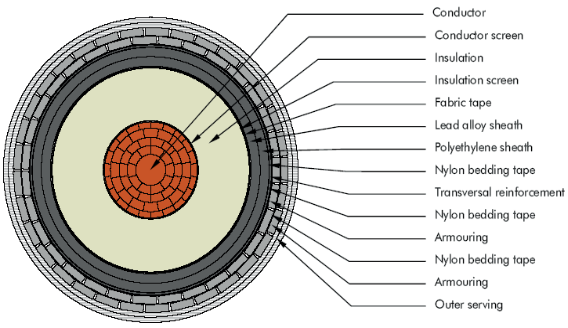


Cable route profile for the Spain-Mallorca HVDC interconnector ("Cometa Project")

Cable Designs

The design of the cables deployed in the Cometa Project has been optimised to be able to install the whole length in one laying campaign.

The HVDC cables have a copper cross section of 750 mm^2. A design with a single layer of flat armour wires was chosen for the shallow part of the route up to 200 m water depth close to both shore ends. For the deeper water middle section, a double flat wire armour layer was used. The figure below shows the cross section of the deep water cable.



Design of the Cometa Project deep water cable

Qualification testing

Type testing of the Cometa Project cables was performed according to the Cigre recommendations published in Electra No. 171 "Recommendations for Mechanical tests on Sub-Marine Cables"[4] and Electra No.189 "Recommendations for Tests of Power Transmission DC Cables for a Rated Voltage up to 800 kV"[5]. Functional tests were performed to make sure that the cable system could be installed and repaired whatever the conditions encountered along the cable route, in shallow water (less than 200 m) as well as at the deepest point (1485 m).

Sea trial

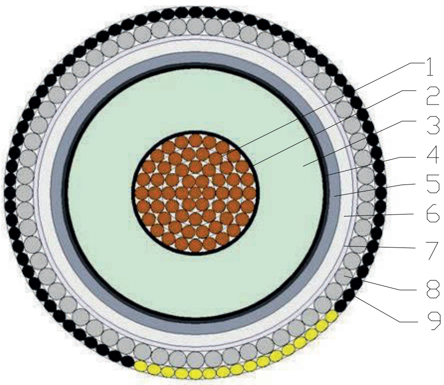
The qualification test program also included a full sea trial on the flexible repair joints on the shallow and deep water cables. Sea trials were performed in shallow water (260 m water depth) and in deep water (at approximately 1500 m water depth). After the sea trials the cables were subjected to a HVDC test at 1.4 times the operating voltage.

Installation and protection

The HVDC cable for the Cometa Project was laid using the Skagerrak vessel. Cables were buried in the sea floor to a water depth of 800m. Protection was performed with a water jetting system.

2.1.3 Extruded Insulation Cables

Extruded insulation cables consist of an inner semi-conducting screen layer, the insulation compound and an outer semi-conducting insulation screen, extruded simultaneously.



1 – Stranded copper conductor, longitudinally sealed
2 – Semiconducting tape+extruded layer
3 – XLPE based special insulation compound
4 - Semiconducting layer + Longitudinal water penetration barrier
5 - Lead alloy sheath
6 - Polyethylene sheath
7 - Polypropylene bedding
8 – Galvanised steel wires armour
9 – Polypropylene serving

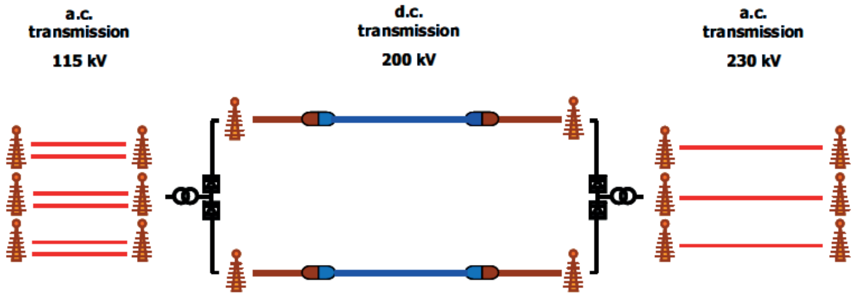
A semi-conducting water swelling tape is then applied between the outer semi-conducting screen and the metallic sheath in order to limit water propagation along the cable core in case of cable damage. The metallic sheath is made of lead alloy, over which a layer of polyethylene compound is extruded. The "armouring" includes bedding, armour and serving, applied in one common process. Armour is made of one layer of galvanised steel wires. Serving is made of polypropylene strings that provide a high degree of abrasion protection and reduce cable friction during laying. Extruded Insulation Cables were deployed in the Trans Bay San Francisco Interconnection.

- *The Trans Bay San Francisco Interconnection ("TBC Project")*

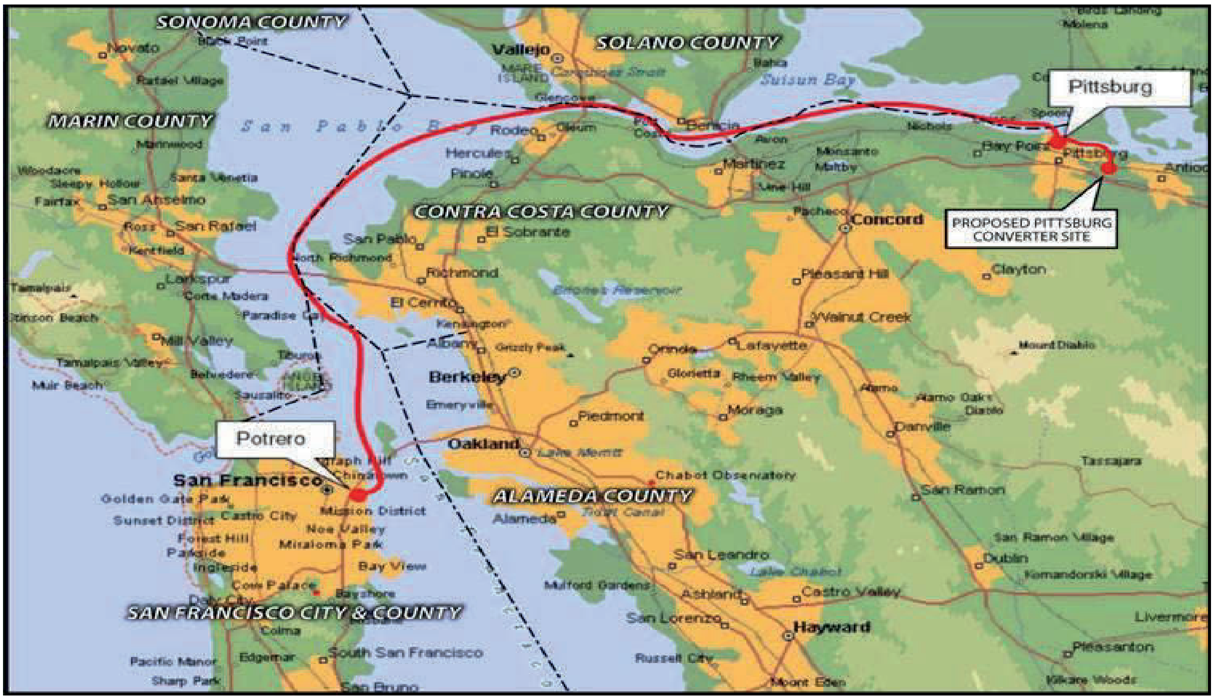
  The Trans Bay Cable Project (TBC Project) is a 400 MW, +/- 200 kV, submarine-based, point-to-point, VSC DC transmission system. It transmits power from the

[4] Electra No. 171 "Recommendations for Mechanical tests on Sub-Marine Cables", 1997
[5] Electra No.189 "Recommendations for Tests of Power Transmission DC Cables for a Rated Voltage up to 800 kV", 2000

generation resource-rich area of Pittsburgh, California to the City and County of San Francisco. Commercial operation was achieved during the first quarter of 2010. The basic project scheme is:

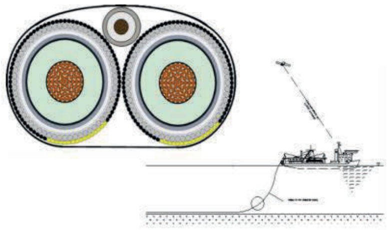


As can be seen from the sketch, the HVDC TBC project is linking a 230 kV AC network from Pittsburgh region to a 115 kV AC network at Potrero station in the city of San Francisco. Route details can be seen below.



The TBC Project makes use of a new generation of HVDC cables, which are insulated with an extruded synthetic compound. In this case, they were considered most appropriate. Environmental and installation conditions led to the cable design with a specific conductor size of 1100 mm^2.
The HVDC cable system was subject to a test program as recommended by CIGRE TB 219[6].

[6] CIGRE TB 219 “Recommendations for testing DC extruded cable systems for power transmission at rated voltage up to 250kV”, 2003



The three cables (two power and one optical cables) were laid and buried simultaneously in a bundle configuration. This methodology provided several advantages:

- reduced installation time
- reduced costs for protection
- and avoid leaving the cable unprotected on the seabed.

The cable system was buried for the entire route length to a target cover depth of 6ft (1.8 meters).


The Giulio Verne installation vessel

The marine cables transport, laying and protection operations were performed using various installation vessels. Due to relatively shallow water in some sections of the route the cable lay was undertaken by two separate laying vessels.

A barge was used for the shallow water section of the route and the cable ship Giulio Verne was used for the deeper water sections.[7]

.

2.2 Connecting offshore platforms with HVDC subsea cables

In addition to serving as an interconnector, HVDC subsea cable systems can also connect offshore substations on platforms to a mainland grid. Offshore platforms can serve different functions: they can either export electricity generated from one or several offshore wind parks to shore or they can serve as a power distribution hub for offshore oil and gas operations. In either case, HVDC subsea cable systems carry the electricity to or from the mainland.

For such connections, the following requirements may apply:

- Possibility to cover long distance (e.g. more than 50 km)
- Possibility to connect to fixed or floating platforms
- Possibility to energise a substation without previous local power supply, so called “Black Start”
- No possibility to insert a redundant system
- Limited dimensions to minimize the environmental footprint

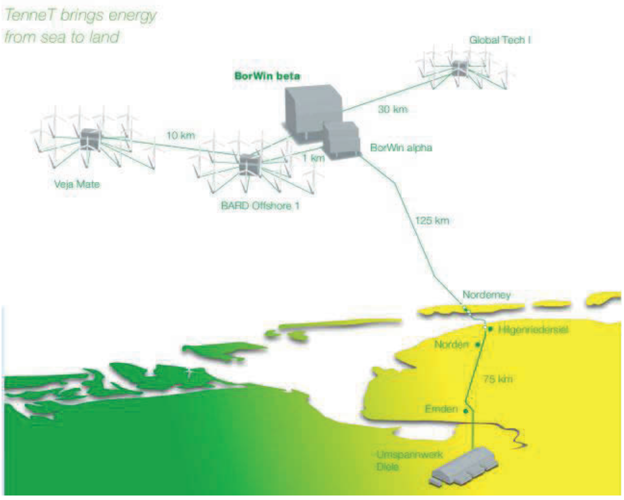

Example of 400 MW offshore substation
Courtesy: Alstom

Due to the above requirements, offshore platforms will only use VSC converter technology. This said, all cable types referenced above for interconnections can also be used for connecting offshore platforms.

As with interconnectors, it needs to be stressed that each HVDC subsea cable system is tailor made for each individual project in order to correspond to the specific project requirements.

[7] More reference can be found in “200 kV DC extruded cables crossing the San Francisco bay”, CIGRE 2010 B1-105.

* *The BorWin 2 Project*



Borwin 2 Project is a large scale offshore wind installation currently under construction in the North Sea located some 120 km north from the German coast. When completed, it will connect one of the most important offshore wind park in the German section of the North Sea.

Borwin 2 will be a bi-pole with two XLPE cables +/- 300 kV for the transmission of 800 MW of power. Route length is 75 km for the HVDC subsea cable laid at a max depth of 50 m, and 90 km for the directly buried land cable. The system will be commissioned the end of 2012

The power produced by the two wind farms will be collected to the offshore converter platform named Borwin beta by means of 155 kV AC submarine cables. On the Borwin beta platform, the VSC system converts 155 kV AC to ±300 kV DC. The power generated by the wind parks is then transmitted to the land converter station by means of extruded DC cables, in particular for the longest and deeper portion of the route it has been designed a cable having the size of 1000 mm2 copper conductor, this cable is jointed to the shallow water cable having the size of 1700 mm2 copper conductor. The submarine HVDC cable route is 125 km long plus additionally 75 km of land route for a total length of the ±300 kV bipole connection of 200 km

The variety of environmental requirements and installation techniques requested have led to an optimization of cable size for the different zones also considering the impact of the installation campaigns on the total project

3. HVDC/HVAC Converter Technology

In Europe, electricity transmission and distribution networks are based on Alternating Current (AC) systems. Hence, when integrating Direct Current (DC) systems into the grid, converter stations are required to convert the DC current and voltage to AC and vice versa. The core component of an HVDC transmission system is the power converter, representing the interface between the AC and DC networks.

Basic concept of HVDC Conversion:

Source: REALISEGRID, 2011

Power converters currently available on the market can be classified in two major categories: Line Commutated Converter (LCC) and Voltage Sourced Converter (VSC). Both technologies have the same ultimate function and both can provide all benefits related to HVDC transmission. This said, they perform in a different way because of the intrinsic differences of power electronic components and therefore have some distinct features highlighted below.

LCC Technology

LCC Converter Station, Courtesy Siemens

Background

- Also called Current Source Converter (CSC)
- in existence since early 1950
- requires connection of two active power networks at either side of link
- typically based on use of power electronic components, so called thyristors

Key characteristics of LCC

- more powerful
- lower losses
- requires robust networks in operation on both sides and therefore is currently the preferred technology for subsea interconnections
- LCC converter stations require more space than VSC depending on the power and therefore are likely to be located on land
- LCC induces more severe working conditions on cables, for such reasons a cable design approved for LCC can also be used with VSC, but not vice versa.

VSC Technology

VSC Converter Station, Courtesy Siemens

Background

- In commercial use since 1999
- Contrary to LCC, it can also be applied for linking isolated networks to the grid, e.g. supply power from generation sources like wind farms or to remote islands.
- Recently developed, compact VSC Multilevel Converters have lower transmission losses and are likely to be the converter type of the future

Key characteristics of VSC

- younger technology
- able of “black start” (i.e. able to start without additional power at one of the two ends)
- currently limited in power (in the order of 1.000 MW) and voltage (up to 500 kV)
- more flexible, smaller and lighter and therefore more suitable for offshore platform installations.

4. Installation of HVDC subsea cables

The installation of HVDC subsea cables is a critical and high technology operation out at sea: it requires experience, dedicated teams and special equipment to be executed without damaging the cable.

During the laying operation it is important to monitor the water depth and current and to control the cable tension, the speed of the laying vessel, the laying route and the laying angle in order to ensure a successful installation.

The laying operation needs to be carefully considered in both, the cable system design and the installation planning.

4.1. The installation vessel

For the installation itself, the cable laying vessel is at the center of the operation. Available cable laying vessels have a cable carrying capacity of 7000 tons on a rotating turntable, and laying machinery capable of more than 50 ton tension. Depending on the cable weight and dimension this typically results in a cable length of around 100 km. For the Cometa Project mentioned above, which used cable with reduced diameter the entire route length of 242 km was laid with one single cable.


The Skagerrak installation vessel

Five powerful thrusters ensure that the dynamic positioning of the vessel is upheld even in severe weather conditions. The system is also mandatory for precise laying required when the subsea cable is to be installed in congested areas, e.g. crossing pipelines.

The vessels are a versatile installation tool, and have equipment for installing fibre optic cable either strapped to the main cable or laid separately at a distance.

With advanced sensors the ‘as-laid data’ and tension are logged continuously during the laying operation. Monitoring of the cable touch down on the sea bed is performed by a remote operated vehicle (ROV) equipped with TV cameras.


Precision laying tool

For cable installation with high water currents, precision laying tools can be used. These tools are remotely operated guide weight systems, attached to the cable and which move along the cable at a certain distance above the sea bed during laying.

With a comprehensive suite of cameras, sonar’s, lights and thrusters, it can be used for exact touchdown monitoring and precision cable guidance.

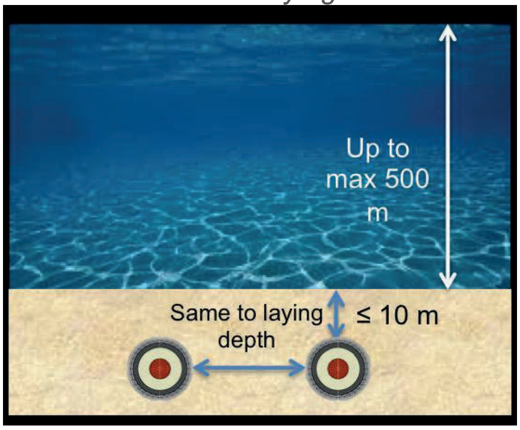
4.2. Subsea cable laying

A distinction needs to be made between cable laying in shallow water (i.e. up to a maximum depth of 500m) and deep water cable laying (i.e. a depth from 500m up to 2.000m). This distinction is mainly a consequence of the risk of mechanical damage along the route:

- For cable systems in shallow waters, burial is mandatory to protect the cable against the risk of damage from fishing gear and anchors;
- For deep water applications, the threats from fishing gear and anchors are non-existing and consequently a burial operation can be largely omitted.

Consequently, cable installation in shallow water may be more expensive than in deep water as cable burial and potential protection measure may have to be accounted for.

HVDC Subsea Cable laying in shallow water



Cable laying in shallow water at up to 500 m.

In shallow water, subsea cables need to be protected against fishing gear and anchors.

Consequently, they will always be buried in the seabed or covered by rocks or protective layers.

In shallow waters, cables may be laid in a bundle configuration or individually. When laid individually, the distance between cables will be at least the water depth.

Foto of a subsea trench

For burying HVDC subsea cables into seabed trenches in shallow waters, different technology options are available.

The "jetting technique" is a fast and efficient way of achieving burial depths of up to 3 meters in soft clay and sand.

Jetting ready for deployment with its launch and recovery system.

The jetting technology fluidises the seabed by opening trenches with 'water swords' which are lowered on either side of the cable into the seabed. As a result of the operation, the HVDC subsea cables sink into the trench.

This burial technique is environmentally friendly as disturbances of the seabed materials are kept at a minimum. The natural movements of the sediments quickly restore the seabed to a natural state.

Technologies allowing opening trenches in a hard soil, including rocks are the following:

Dredging Machine

Wheel trenching Machine

Chain trenching Machine

Rocky, hard sea beds represent a challenge to subsea cable burying. If alternative routings are not possible trenching technologies have to be used to bury the cable. Short- term these impact the seabed environment. Mid- to long term the natural flora recovers.

In principle, the protection level required for cables on the seabed is expressed as the 'Burial Protection Index' (BPI). The BPI indicates the relative protection burial efforts necessary depended on the possible threat of external damage to the cable. This threat is dependent upon the type of soil, seabed conditions and shipping activities above the cable route. According to the threat identified, the BPI will specify the burial depths and methods.[8]

The figure below shows the required burial depth to protect the cables from different objects as function of composition of the sea floor.

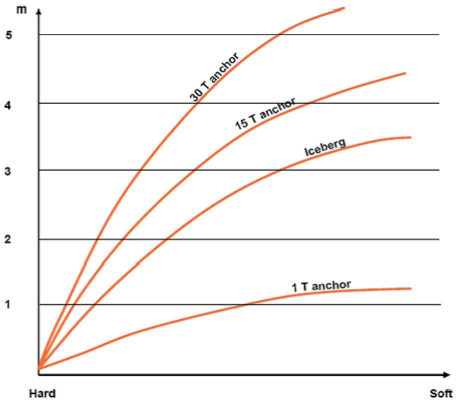


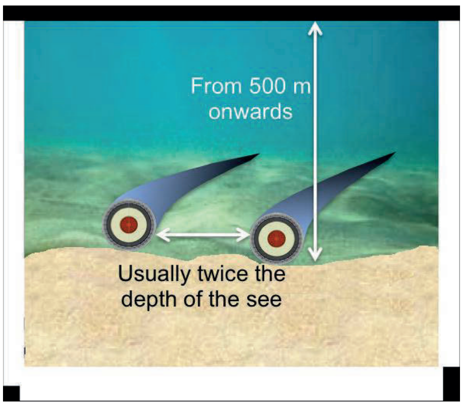
Figure 6.2 Anchor penetration versus soil harness

Threat	Hard ground (clay >72kPa, rock)	Soft-firm soils (sand, gravel, clay 18-72kPa)	Very soft-soft soils (mud, silt, clay 2-18kPa)
Trawl boards, beam trawls, scallop dredges	<0.4m	0.5m	>0.5m
Hydraulic dredges	<0.4m	0.6m	N/a
Stow net fishing anchors	N/A	2.0m	>2.0m
Ships' anchors up to 10,000t DWT (50% of world fleet)	<1.5m	2.1m	7.3m
Ships' anchors up to 100,000t DWT (95% of world fleet)	<2.2m	2.9m	9.2m

Table 1. Nominal required burial depths to place cable below threat line for different threats and soils (these figures include a 33% safety factor on actual threat penetration)

Required burial depth for protection as function of soil composition, from[9]
also see CIGRE Technical Brochure 398

HVDC Subsea Cable laying in deep water



Cable laying in deep water from 500 m onwards

In deep water, i.e. from 500 m onwards, subsea HVDC cables will simply be laid on the seabed.

In most cases, they are laid individually with the distance between the cables usually amounting to twice the depths of the sea. This requirement results from the need to recover the cable in case of damage and to avoid any overlapping. In terms of laying operation, it is to be noted that in deep waters each cable will be laid in a single laying operation.

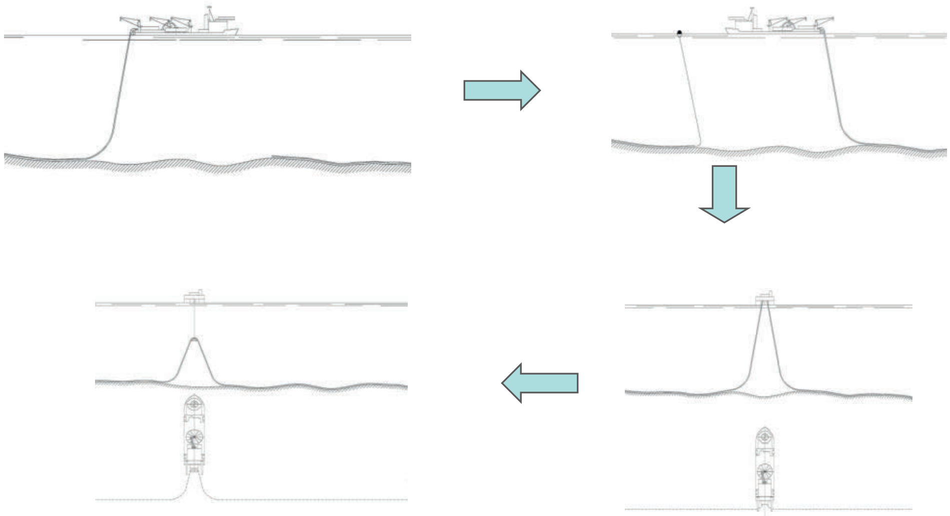
8 CIGRE technical brochure 398, Third party damage to underground and submarine cables, 2009

9 R. Hoshina and J. Featherstone, "Improvements in Submarine Cable System Protection", Submarine Cable Improvement Group, http://www.scig.net/.

Over time, they will be covered with by the local environmental segments including sand and mussels which do not affect the operation of the cable. In return the cable has no impact on the environment.

4.3. Repair of deep water cable links

Subsea HVDC cable system repairs are relatively infrequent and are almost always due to external mechanical damage to the cable. When necessary, they are a highly complex and costly undertaking: A complete repair consists of fault location, cutting, recovering, in line joint, laying spare cable, joint to the second cable end and laying a ‘omega loop’. This procedure can be applied in water depths up to approximately 500m. For deeper water, special procedures apply.

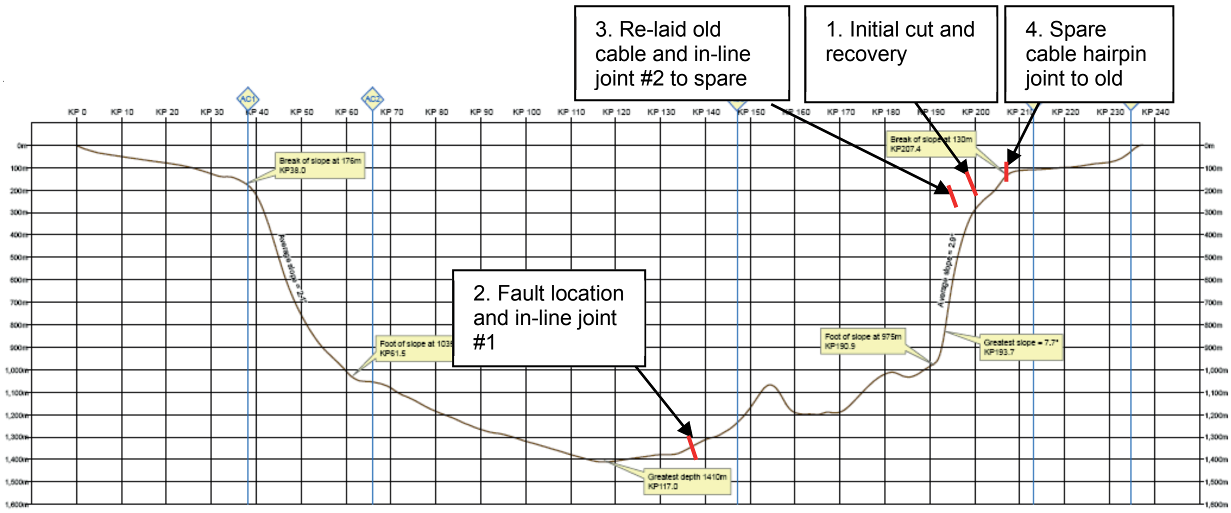


Repair procedure for HVDC subsea cable:

1. Cut the cable, leave one end at sea bed and lift other end to surface
2. Joint surface end with spare cable
3. Lift second cable to surface and join with spare cable
4. Lower entire cable to the seabed forming the ‘omega loop’

Deep water repair operations may require special equipment (remotely operated vehicle cutting devices and clamps for pulling the cable from the seabed). Furthermore, mechanical stresses resulting from the operation on the cable are likely to be too large for ordinary cable repair vessels and may require special boats.

The figure below shows the principles for a repair of a fault at very deep water.



Principle for repair of a fault in very deep waters

5. Environmental aspects of HVDC subsea cable systems

Impact on Sea bed / the Sea

As any electricity transmission cable, also HVDC subsea cable systems may have a thermal impact on the sea bed in which it is buried in shallow water installation. During operation, the temperature of the cable will rise dependent on the current carried and the load factor. Heat distribution to surrounding soil depends on the soil type. The impact of heat release on soil temperature is strictly local and very limited. These impacts are to be taken into account during the design of the cable system if there are local requirements.

In any case, the sea water will not be affected by any possible soil heating.

Landing of HVDC subsea cable systems on shore

Depending on local requirements, on shore landing of HVDC subsea cable systems and their connections to the land transmission networks differ among EU Member States. Europacable member companies comply with all prevailing requirements. Cable and installation design can be adapted to minimize the impact on the ecosystem during installation and operation.

Electro Magnetic Fields (EMF)

HVDC subsea power transmission generates continuous magnetic fields comparable to natural static magnetic fields around the cable. In the marine environment possible local regulations regarding requirements on maximum compass deviation have to be taken into consideration for the cable system design.

6. Availability of HVDC subsea cable systems

Today, mass impregnated HVDC subsea cables are available up to +/- 600 kV at 2,200 MW and XLPE HVDC cables up to +/- 320 kV at 1,000 MW. Increases in voltage and capacity can be expected in the near future.

As regards other components required for HVDC systems, converter stations are fully available.

Future meshed HVDC networks will require the use of circuit breaker technology, so called switchgear, which is currently in its final development phase. It is expected that this last bottleneck will be removed in the near future, enabling the operation of meshed HVDC systems in Europe.

7. Reliability of HVDC subsea cable systems

HVDC transmission systems are composed of two main components, the converter station and the cable system. For the purpose of this paper we will focus on the reliability of HVDC submarine transmission cable systems, leaving aside considerations on the reliability of conversion stations which are mainly based on power electronics and are not part of the core competence of Europacable members.

HVDC connections require a high level of reliability: this is firstly due to the high cost of repairing of submarine cables. Secondly, HVDC transmission systems are often considered as an equivalent to a power generating station or power load. Contrary to large meshed AC transmission systems, there is often no redundancy in HVDC systems and the HVDC transmission system is the only power source capable to feed a certain user such as remote islands, offshore platforms or wind farms. Consequently, the non-availability of such power source may represent a risk for black out, hence requiring high level of reliability.

HVDC subsea cable systems are carefully checked before delivery and commissioning: Following production, HVDC subsea cables and all system components undergo a thorough verification procedure and routine tests to confirm compliance with homogenous quality according to international recommendations. Following installation, the cable system is subject to a commissioning test to confirm proper installation before being placed in operation.

Various CIGRE studies demonstrate the high reliability of HVDC subsea transmission cable systems, clearly differing between external and internal failure origins.

For mass impregnated (MI) cables CIGRE Technical Brochure 379[10] stipulates that no failures of internal origin can be identified in HVDC subsea cables (total installed circuit length of 2687km) during the period 1990 – 2005. During the same period a total of 18 failures of external origin have been registered.

In view of these findings, increasing care is taken to improve the protection of HVDC subsea cable system against external damages which are depending on the local marine situation: Especially in shallow waters (up to 500 m) where the risk of damage is very high, it is recommended to bury or protect the cable. Burying the cables at a depth of 1 to 5 meters has greatly reduced the number of external damages. Where burying is not possible, alternative protection such as rock dumping or covering the cable with concrete mattress can be considered. CIGRE Technical Brochure 398[11] offers an overview of procedures and precautions that may be adopted to limit the risk of mechanical damages caused by third parties on submarine cables.

As *extruded HVDC subsea cable systems* are a relatively new transmission technology, only limited evidence based data regarding long term reliability is currently available. This said, *CIGRE Technical Brochure* 379[12] includes a survey of 226 km circuit length of extruded insulation HVDC subsea cables (150 kV) registering no failures during the first three years of operation of subsea cables which were covered by the time of publication. Furthermore, new projects are closely monitored and no failures of any origin in the installed cables in service have been reported up to now. The installed HVDC extruded subsea cables are reported in the reference list under Chapter 10.[13]

In order to accompany and to continue with the introduction of extruded HVDC subsea cable technology, Europacable strongly recommends strict compliance with pre-qualification requirements as defined by CIGRE recommendations. As seen from experience to date, strict compliance with pre-qualification requirements issued by CIGRE expert committees will lead to the introduction of reliable transmission technology.

Repair time

Quantifying time needed to repair failures of HVDC subsea cables is a complex exercise, depending on type of fault, vessel and crew availability and notably weather conditions.

Given the series of factors that may vary on a case by case basis it is not possible to provide general estimations on repair duration. However, the following observations can be made. As any HVDC subsea cable will be tailor made for the specific project application, one of the most important requirements to reduce outage duration is the storage of spare parts.

---

[10] CIGRE Technical Brochure 379 “Update of service experience of HV underground and submarine cable systems”, 2009

[11] CIGRE Technical Brochure 398 “Third-Party Damage to Underground and Submarine Cables”, 2009

[12] CIGRE Technical Brochure 379 “Update of service experience of HV underground and submarine cable systems”, 2009

[13] HVDC extruded cables installed comply with the unique internationally recognized reference CIGRE Technical Brochure 219 which defines testing criteria for the qualification of extruded HVDC cable systems up to +/- 250 kV. Recently the new CIGRE Technical Brochure 496 “Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to 500 kV” has been published. Mass impregnated HVDC cables are also covered by CIGRE recommendation as reported in ELECTRA 189 up to the voltage of +/- 800 kV.

Provided spare parts are available, reparation procedures may include the following steps:

- Fault identification: Fault localisation may be less difficult if damage has been caused by an anchor of vessel on site, yet more complex if it has been caused by an unknown fishing operation.
- Definition of appropriate repair procedure dependent on type of damage (depth, position from the coast or terminations, etc)
- Identification and contracting of appropriate repair vessel and displacement of vessel and crew to repair site
- Consideration of weather conditions

8. Integration of HVDC subsea cable systems into AC transmission networks

As mentioned above, from a transmission system perspective, HVDC subsea cable systems can be considered as an equivalent to a power generating station or power load. Consequently, integrating them into existing AC transmission networks requires careful consideration.

Europacable recommends taking the following aspects into account:

- The feeding network needs to have the capability to sustain the power demand;
- The fed network needs to have the capability to receive and transmit the due power;
- The systems need to fulfil the N-1 security criterion, i.e. connected networks need to be able to sustain the HVDC contingency without extremely negative consequences. The feeding network needs to be able to sustain the sudden loss of load and the fed network needs to be able to survive after the loss of power.
- LCC and VSC converter technologies have different impacts on the connected networks: LCC converter require robust networks able to provide the reactive power and to reduce the risk of commutation failure; VSC converter have minor impact on this regard.

In order to evaluate the transmissible power from the production or from redundant sites to the utilization sites, the availability of an extended and optimized transmission grid is of paramount importance. This will play an important role in relation to the security of supply and for a progressive integration of an extended electric market.

One particularity of DC transmission is that the load flow can be taken into control simply through the voltage regulation whereas it is more complex for AC transmission systems.

9. Cost Aspects of HVDC subsea cable systems

Respecting EU competition requirements, Europacable can only provide general statements regarding cost factors of HVDC subsea cable systems. Also each project is unique and a full macroeconomic assessment of the HVDC subsea cable system should be made, considering full life cycle costs including: installation, maintenance, impact on land / property, environmental protection etc. Principally, Europacable believes that the following two dimensions should be taken into account:

Cost of installation

- The cost of installing a HVDC subsea cable system will depend on the specific requirements defined for the system. In addition to the subsea cable itself, accessories like joint bays, transition stations, converter stations etc. need to be taken into account.
- Subsea installation costs are furthermore dependent on a variety of factors including route, length, laying depths, condition and nature of the sea bottom.
- Installation costs also need to include specific measures taken to protect the subsea cable in shallow waters against external impacts resulting from external dangers such as anchoring or fishing.

- Subsea cable systems also include submarine-to-land transition cable systems. (Please see Europacable HVDC underground cable documentation.)

Cost of operation

- With very low transmission losses, the cost of operation of HVDC subsea cable system is negligible.
- Subsea HVDC cables require practically no maintenance. Due to possible seabed movements, inspections may be necessary from time to time.

10. HVDC underground and submarine cable systems in operation

The table below provides an overview of the major HVDC subsea cable projects realized up to now and currently in operation:

Name of Link	Date	Voltage (kV)	Power (MW)	Nbr of Cables	Route Length (km)	Cable Length (km)	Water Depth (m)	Type
Gotland 1	1953	100	20	1	100	100	160	MI- CSC
Konti-Skan 1a	1964	285	300	1	64	64	80	MI- CSC
Italy – Sardinia	1965	200	100	2	118	236	450	MI- CSC
Vancouver Is. 1	1969	300	156	3	27	81	200	MI- CSC
Kontskan 1b	1974	285	300	1	32	32	80	MI- CSC
Skaggerak 1,2	1976	263	250	2	125	250	600	MI- CSC
Vancouver Is. 2	1976	300	185	2	35	70	200	MI- CSC
Gotland 2	1983	150	160	1	95	95		MI- CSC
Cross-Channel 2	1986	270	250	8	50	400	55	MI- CSC
Gotland 3	1987	150	160	1	97	97	160	MI- CSC
Konti-Skan 2	1988	285	300	1	64	64	80	MI- CSC
Konti-Skan 3	1988	285	300	1	64	64	80	MI- CSC
Fenno-Skan I	1989	400	500	1	200	200	117	MI- CSC
Cook Strait 2	1991	350	500	3	40	120	300	MI- CSC
Skagerrak 3	1993	350	500	1	125	125	500	MI- CSC
Cheju (Korea)	1993	180	300	2	96	192	160	MI- CSC
Baltic Cable	1994	450	600	1	250	250	60	MI- CSC
Sweden - Poland	1999	450	600	1	253	253	90	MI- CSC
Italy - Greece	2001	400	500	1	160	160	1000	MI- CSC
Italy - Greece	2001	400	500	1	40	160	Land	SCFF-CSC
Moyle (UK)	2001	250	500	2	55	110	100	MI- CSC
Bass Link (Aus)	2005	400	500	1	290	290	75	MI- CSC
New Jersey-Long Island (Neptune)	2007	500	660	1	84	84	25	MI- CSC
NorNed Norway-Netherlands	2007	450	700	2	580	1160	410	MI- CSC
Sardinia-Italy	2009	500	1000	2	420	420	1650	MI- CSC
Storebaelt - Denmark	2010	400	600	1	56	56	60	MI- CSC
Cometa (HVDC) - Spain	2011	250	400	2	247	494	1485	MI- CSC
BritNed Netherland - UK	2011	400	1000	2	260	520	60	MI- CSC
Cook Strait 1	1965	250	300	3	39	117	300	PIGF- CSC
Hokkaido/Honshu	1980	250	150	2	42	84	290	SCFF-CSC
KII Channel Japan	2000	500	2800	4	49	196	70	SCFF-CSC
Cross Sound (USA)	2002	150	330	2	42	84	40	XLPE- VSC
Troll 1,2	2004	60	88	4	70	280	250	XLPE- VSC
Estlink I	2006	150	350	2	105	210	Land+Sea	XLPE- VSC
Transbay S Francisco USA	2009	200	400	2	85	170	35	XLPE- VSC
HVDC BorWin 1 - Germany	2009	150	400	2	125	250	50	XLPE- VSC
HVDC BorWin 1 - Germany	2009	150	400	2	75	150	Land	XLPE- VSC

11. Projects of HVDC underground and submarine cable systems under construction
The list below provides an overview of the major HVDC subsea cable system projects currently under construction.

BORWIN 2

- Connection of one of the most important offshore wind park in the German section of the North Sea. Borwin 2 will be a bi-pole with two XLPE cables +/- 300 kV for the transmission of 800 MW of power. Route length is 75 km for the HVDC subsea cable laid at a max depth of 50 m, and 90 km for the directly buried land cable. The system will be commissioned the end of 2012.

SYLWIN 1

- Connection of the largest offshore wind park in the German section of the North Sea. Sylwin 1 will be a bi-pole with two XLPE cables +/- 320 kV for the transmission of 900 MW of power. Route length is 159 km for the HVDC subsea cable laid at a maximum depth of 50 m, and 45 km for the directly buried land cable. The system will be commissioned in the end of 2014.

SKAGERRAK 4

- Skagerrak 4 will be the first VSC connection at a voltage of +/- 525 kV with a monopole MI cable of 700 MW. The submarine part of the cable is 137 km long laid at a maximum water depth of 600 m, and the underground directly buried portions in Denmark and Norway are 92 + 13 km respectively. The system will be commissioned in the end of 2014.

WESTERN LINK UK

- Western Link UK will be the most powerful HVDC connection ever realized and will connect the Scotland (in proximity of Glasgow) to England (in proximity of Liverpool or northern Wales border). The connection will be a bi-pole with two MI PPL cables +/- 600 kV for the transmission of 2200 MW of power, the length of the submarine cable route is 370 km at a maximum water depth of 350 m, the length of the underground route is 40 km. The system will be commissioned in the end of 2015.

For further information please visit our website www.europacable.com or contact:
Dr. Volker Wendt, Director Public Affairs, Europacable, v.wendt@europacable.com

About Europacable
Founded in 1991, Europacable represents 85% of the European wire and cable industry. Our member companies include European multinationals providing global technology leadership, as well as over 200 highly specialized small- and medium sized producers of energy, telecommunication and data cables. In 2009, the industry had a total consumption of €20 billion in wire & cables resulting in the manufacture in Europe alone of some 38 million km of cables. Europacable is listed in the European Commission's transparency register under: 453103789-92.