Docket No. _____
Exh. TDI-LE-3

HVDC Light®
It's time to connect

ABB

1 Introducing HVDC

1.1 This is HVDC

High-voltage direct current (HVDC) transmission is a safe and efficient technology designed to deliver large amounts of electricity over long distances. HVDC was first developed during the 1930s by ASEA, the Swedish electrical conglomerate and one of the founders of ABB.

For many years HVDC engineers looked for a reliable converter technology that could effectively switch AC electricity produced at the point of generation into DC electricity for transmission, and then convert it back to AC again at the other end of the line so it could run motors, lights, etc. By the early 1950s research into mercury-arc technology, led by ASEA engineer and HVDC pioneer Uno Lamm, had made such progress that ASEA could build the world's first commercial HVDC power link between the Island of Gotland and the Swedish mainland. Since then, HVDC transmission systems have been installed in many parts of the world.

1.2 The benefits of HVDC

HVDC systems can transmit more electrical power over longer distances than an similar AC transmission system, which means fewer transmission lines are needed, saving both money and land. In addition to significantly lowering electrical losses over long distances, HVDC technology is also very stable and easily controlled, and can stabilize and interconnect AC power networks that are otherwise incompatible.

The HVDC market is growing rapidly and has become an important part of many transmission networks, not least because it can connect remote sources of electrical power – often emissions-free renewable sources like hydro or wind generation – to load centres where it is needed, hundreds or even thousands of kilometers away. Once installed, HVDC transmission systems often form the backbone of an electric power system, combining high reliability with a long, useful life. Their core component is the power converter, which serves as the interface with the AC transmission system. The conversion from AC to DC, and vice versa, is achieved by controllable electronic switches (called valves).

1.3 The development of HVDC technology

Today there are two main technologies. HVDC Classic, the first developed technology, is used primarily for bulk electrical transmission over long distances, overland or subsea, and for interconnecting separate power grids where conventional AC methods cannot be used. Today there are more than 100 HVDC installations in all parts of the world. A classic HVDC transmission typically has a power rating of more than 100 megawatts (MW) and many are in the 100 – 10,000 MW range. They use overhead lines, or undersea/underground cables, or a combination of cables and lines.

HVDC Light®, developed by ABB and launched in 1997, is an adaptation of HVDC classic used to transmit electricity in power ranges (from 50 – 2,500 MW) transmitted using overhead lines or invisibly, using environmentally friendly underground and subsea cables. It is used for grid interconnections and offshore links to wind farms and oil and gas platforms. In both HVDC Classic and HVDC Light®, it is possible to transmit power in both directions and to support existing AC grids in order to increase robustness, stability and controllability.

1.4 The development of HVDC Light® technology

The HVDC Light® technology, developed by ABB and based on voltage source converters (VSC), has evolved since its introduction in 1997. When the technology's first generation was introduced it had the same functionality as HVDC Light® today, but with relatively high losses. The focus of development over the years has been to maintain functionality and reduce losses in order to make it more economical.

The two-level converter valve together with custom designed series-connected press-pack insulated-gate bipolar transistors (IGBTs produced by ABB) have been the cornerstone of HVDC Light® since the first generation. The technology is now in its fourth generation, and technical developments have made it possible to handle higher DC voltages applying a cascaded two-level converter (CTL). Technology modules developed and refined during the last 15 years have made it possible to create a converter that addresses and solves many of the limitations of VSC-HVDC transmission, while retaining operational functionality and reduced losses.

1.5 Market outlook

Energy infrastructure is an essential building block of our society. Ambitious climate change goals, strong global demand for electricity and aggressive economic growth targets will not be achievable without a major shift in the way infrastructure is developed.

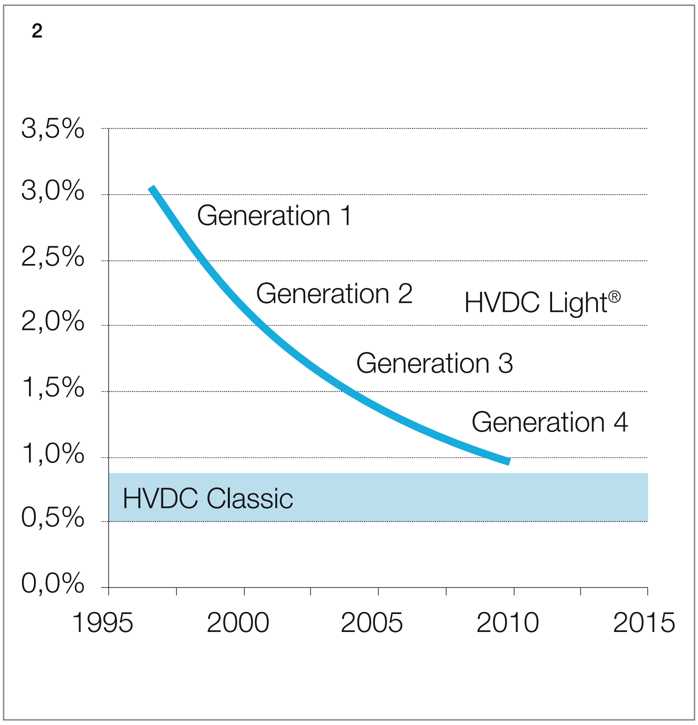
Integrated and reliable transmission networks are a crucial prerequisite for developing integrated energy markets, enhancing security of supply, enabling the integration of renewable energy sources, and increasing energy efficiency.

The VSC technology market has grown rapidly in recent years to fulfill these goals. Thanks to its technical properties, it has been selected for a number of transmission projects aimed at interconnecting European energy markets by means of undergrounding, integrating remote renewable energy sources such as wind farms at sea, and in applications like power from shore, which strives to further decarbonize our environment.

As transmission capacity has been increased and electrical losses reduced, HVDC Light® technology has the right properties to become the natural choice for future transmission projects. VSC technology is a prerequisite to solving many of the energy system challenges of the future. It has the right properties to support:

- Further integrating remote renewables such as hydro, wind and solar generation into the energy system
- Stabilizing transmission grids with large shares of volatile generation in the power networks
- Facilitating energy sharing and trading by interconnecting energy markets
- Overcoming limits in new right-of-way by land and sea cable transmission and AC to DC conversion in existing overhead line corridors
- Enabling remote load connections such as offshore platforms and mining sites
- Feeding electricity into densely populated urban centers
- Constituting the backbone of a DC grid to transmit bulk power through congested areas

1 The Gotland 1 valve hall from the 1950's. | 2 Losses for HVDC Light® have decreased for each generation.



In the following section, the functionality of HVDC Light® will be demonstrated in more detail.

1.6 Can HVDC support renewable energy systems?

Alternatives to burning fossil fuels for electricity, including hydro, wind and solar generation, are often located in remote, hostile locations and need robust electrical transmission systems to ensure high availability, minimal maintenance and of course, low losses. HVDC transmission systems offer the best technical and economical long distance transmission solutions, integrating volatile renewable generation, and stabilizing power networks.

1.7 What else can HVDC do?

There are numerous ways to use HVDC transmission. For example, HVDC systems deliver electrical power to remote loads such as offshore platforms, and mining sites. In addition to reliably delivering electricity generated from mountaintops, deserts and seas across vast distances with low losses, HVDC systems can stabilize problems in AC networks and improve grid performance in the event of power disturbances. HVDC systems are ideal for feeding electricity into densely populated urban centers, and for interconnecting separate power networks to facilitate energy sharing and trading.

2 This is HVDC Light®

There are a number of criteria which help to decide which technology is best suited for a particular customer application, including investment costs (capital expenditure), system losses, system availability, power and voltage levels, means of transmission, availability of land and AC network support.

In the following sections it will be explained what advantages customers can obtain from the unique properties of HVDC Light®.

2.1 Independent power transfer and power quality control

The HVDC Light® system allows fully independent control of both the active and the reactive power flow within the operating range of the HVDC Light® system. The active power can be continuously controlled from full power export to full power import. Normally each station controls its reactive power flow independently of the other station. However, the flow of active power to the DC network must be balanced, which means that the active power leaving the DC network must be equal to the active power coming into the DC network, minus the losses in the HVDC Light® system. A difference in power would imply that the DC voltage in the system would rapidly increase or decrease, as the DC capacitors change their voltage with increased or decreased charge. To attain this power balance, one of the stations controls the DC voltage. This means that the other station can arbitrarily adjust the transmitted power within the power capability limits of the HVDC Light® system, whereby the station that controls the DC voltage will adjust its power to ensure that the balance (i.e. constant DC voltage) is maintained. The balance is attained without telecommunication between the stations, but simply on the measurement of the DC voltage.

2.2 Absolute and predictable power transfer and voltage control

The active power flow can be determined either by means of an active power order or by means of frequency control in the connected AC network. The converter stations can be set to generate reactive power through a reactive power order, or to maintain a desired voltage level in the connected AC network. The converter's internal control loop is active and reactive current, controlled through measurement of the current in the converter inductor and using orders from settings of active and reactive power which an operator can make. In an AC network, the voltage at a certain point can be increased or reduced through the generation or consumption of reactive power. This means that HVDC Light® can control the AC voltage independently in each station.

2.3 Low power operation

Unlike HVDC Classic converters, the HVDC Light® converter can operate at very low power, or even zero power. The active and reactive powers are controlled independently, and at zero active power the full range of reactive power can be utilized. In this way the HVDC Light® converter can operate as a SVC, Static VAr Compensator.

2.4 Power reversal

An HVDC Light® transmission system can transmit active power in either of two directions with the same control setup and with the same main circuit configuration. This means that an active power transfer can be quickly reversed without any change of control mode, and without any filter switching or converter blocking. The power reversal is obtained by changing the direction of the DC current and not by changing the polarity of the DC voltage as for HVDC Classic. The speed of the reversal is determined by the network. The converter could reverse to full power in milliseconds if needed. The reactive power controller operates simultaneously and independently in order to keep the ordered reactive power exchange unaffected during power reversal.

2.5 Reduced power losses in connected AC systems

By controlling the grid voltage level, HVDC Light® can reduce losses in the connected grid. Both transmission line ohmic losses and generator magnetization losses can be reduced. Significant loss reductions can be obtained in each of the connected networks.

2.6 Increased transfer capacity in the existing system

Voltage increase

The rapid and accurate voltage control capability of the HVDC Light® converter makes it possible to operate the grid closer to the upper limit. Transient overvoltages would be counteracted by the rapid reactive power response. The higher voltage level would allow more power to be transferred through the AC lines without exceeding the current limits.

Stability margins

Limiting factors for power transfer in the transmission grid also include voltage stability. If such grid conditions occur where the grid is exposed to an imminent voltage collapse, HVDC Light® can support the grid with the necessary reactive power. The grid operator can allow a higher transmission in the grid if the amount of reactive power support that the HVDC Light® converter can provide is known. The transfer increase in the grid is larger than the installed MVA capacity of the HVDC Light® converter.

2.7 Powerful damping control using P and Q simultaneously

As well as voltage stability, rotor angle stability is a limiting factor for power transfer in a transmission grid. HVDC Light® is a powerful tool for damping angle (electromechanical) oscillation. The electromechanical oscillations can be rather complex with many modes and many constituent parts. It is therefore not always possible to find robust damping algorithms that do not excite other modes when damping the first ones. Many control methods that influence the transmission capacity can experience difficulties in these complex situations. Modulating shaft power to generators, switching load demand on and off, or using an HVDC Light® system connected to an asynchronous grid are methods that can then be considered. The advantage of these methods is they actually take away or inject energy to damp the oscillations.

HVDC Light® is able to do this in several ways:

- by modulating the active power flow and keeping the voltage as stable as possible
- by keeping the active power constant and modulating the reactive power to achieve damping (SVC-type damping)

Line current, power flow or local frequency may be used as indicators, but direct measurement of the voltage angle by means of Phasor measurements can also be used.

2.8 Fast restoration after blackouts

HVDC Light® can aid grid restoration in the event of power disruptions, when voltage and frequency support are much needed. This was proven during the August 2003 blackout in the Northeastern U.S by the excellent performance of the Cross Sound cable link that interconnects Connecticut and Long Island. In the event of a power disruption, a black-start capability can be implemented in HVDC Light® systems. This can help an HVDC Light® operator speed up grid restoration, because the lack of energy (typically in the first 6-24 hours) may initiate considerably higher prices for energy. This black-start facility is implemented on the Estonian side of the Estlink HVDC Light® project.

2.9 Islanded operation

The HVDC Light® converter station normally follows the AC voltage of the connected grid. The voltage magnitude and frequency are determined by the control systems of the generating stations. In the event of a voltage collapse or "black-out," the HVDC Light® converter can instantaneously switch over to its own internal voltage and frequency reference and disconnect itself from the grid. The converter can then operate as an idling "static" generator, ready to be connected to a "black" network to provide the first electricity to important loads. The only precondition is that the converter at the other end of the DC cable is unaffected by the black-out.

HVDC Light® station.

2.10 Flexibility in design

The HVDC Light® station consists of three parts:

- The DC yard, with DC cable or DC overhead line interface
- The converter of modular design, with the IGBT valves and the converter reactors
- The grid interface, with power transformer and switches

The different parts are interconnected with HV cables, which make it easy to separate the parts physically, so as to fit them into available sites.

HVDC Light® can be implemented in back-to-back stations, as transmission systems with DC cables or overhead lines.

2.11 Undergrounding

HVDC Light® employs HV cables for DC power transmission that are well suited for undergrounding. The cables are buried all the way into the DC part of each converter building. When the landscape has been restored after the cable laying, the transmission route quickly becomes invisible.

2.12 No relevant magnetic fields

The two HVDC Light® cables can normally be laid close together. As they carry the same current in opposite directions, the magnetic fields from the cables more or less cancel each other out. The residual magnetic field is extremely low, comparable to the level of the earth's magnetic field. Magnetic fields from DC cables are static fields, which do not cause any induction effects, as opposed to the fields from AC cables and lines.

The electromagnetic field around an HVDC Light® converter installation is quite low, since all apparatus is located in a building designed to provide a very efficient shield. The shielding is needed to minimize emissions in the radio frequency range, i.e. radio interference. The background is that in HVDC Light® high currents are switched, giving high internal current derivatives. Such switchings generate frequencies that might cause radio interference if not properly controlled and shielded. Considering these conditions, the overall and detailed design has been aimed at ensuring proper mitigation of radio interference and corresponding fields. The electromagnetic field levels around the installation are therefore well below the values stipulated in the relevant standards for human exposure. The electromagnetic emission is verified through measurements. The HVDC Light® converter installation is connected to the AC power grid/system through AC overhead lines or AC cables. Normally, current harmonics from the converter are negligible and no harmonic filters are needed on the output lines. This means that they can be considered as normal AC lines/cables installed within the power grid/system.

2.13 Low environmental impact

The fact that no electric or magnetic clearance from the cables is needed, and that the converter stations are enclosed in a building, makes the impact of the transmission system on the environment very low. The building can be designed to resemble other buildings in the neighborhood, and the cables are not even visible. Environmental considerations have a strong influence in the design, the choice of material and the manufacturing processes. Metals and insulation materials are used in a way that is easy to recycle.

2.14 Indoor design

To avoid tall steel supporting structures, to facilitate maintenance and to improve personal safety, converter reactors and DC yard equipment are mounted directly on low foundations/supports and kept within a simple warehouse-style building with lockable gates and doors. The building will keep high-frequency emissions and acoustic noise low and protect the equipment from adverse weather.

2.15 Short time schedule

The converter valves and associated control and cooling systems are factory assembled in transportable modules. This ensures rapid installation and on-site testing of the core systems.

The building is made up of standardized parts, which are shipped to the site and quickly assembled. A typical delivery time from order to hand-over for operation can be 20 months, depending of course on local conditions for converter sites and cable route.

Cable laying.

1 HVDC Light® (power from 50 – 1,200 MW) | 2 HVDC Classic (power up to 8,000 MW).

2.16 Comparison of DC and AC cable systems

DC cable system
- No limit on cable length
- No intermediate station needed
- No increase of capacitance in the AC network (avoids low-order resonances)
- Lower losses

AC cable system
- Cable capacitance limits the practical cable length
- Reactive compensation is needed

2.17 Comparison of HVDC Light® and HVDC Classic

HVDC Light® (power from 50 – 2,500 MW)
- Each terminal is an HVDC converter plus an SVC
- Suitable both for submarine and land cable connections
- Advanced system features
- Footprint (e.g. 1,200 MW): 100 x 150 x 20 meters
- Short delivery time

HVDC Classic (power up to 8,000 MW)
- Most economical way to transmit power over long distances
- Long submarine cable connections
- Around three times more power in a right-of-way than overhead AC
- Footprint (e.g. 600 MW): 200 x 120 x 22 meters

HVDC Light

IGBT used as active component in valves
- Multi-chip design
- Forward blocking only
- Current limiting characteristics
- Gate turn-off and fully controllable; forced commutation
- High-speed device

The pulse width controls both active and reactive power
- The IGBT can be switched off with a control signal; fully controllable
- Forced commutation up to 2,000 Hertz (Hz)

1 AC and DC voltage characteristics I 2 Simplified single-line diagram for HVDC Light® I 3 HVDC Light® deep sea cables I 4 An HVDC Light® transmission system can control both active and reactive power.

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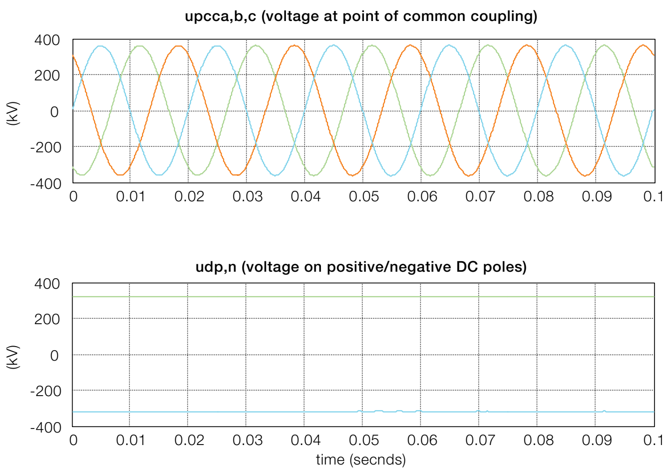
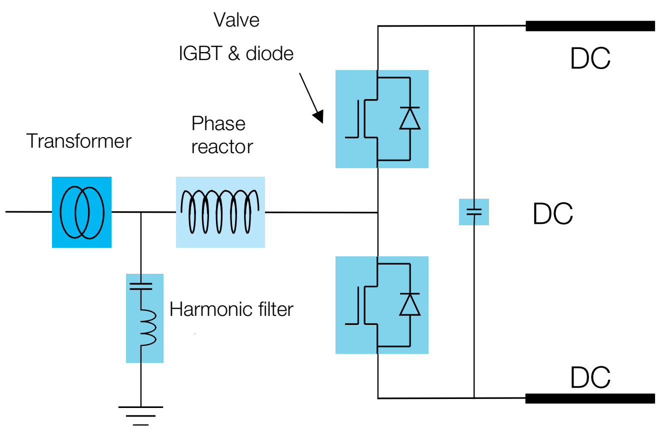


- Upper trace: transformer voltage
- Lower trace: DC Voltage

2



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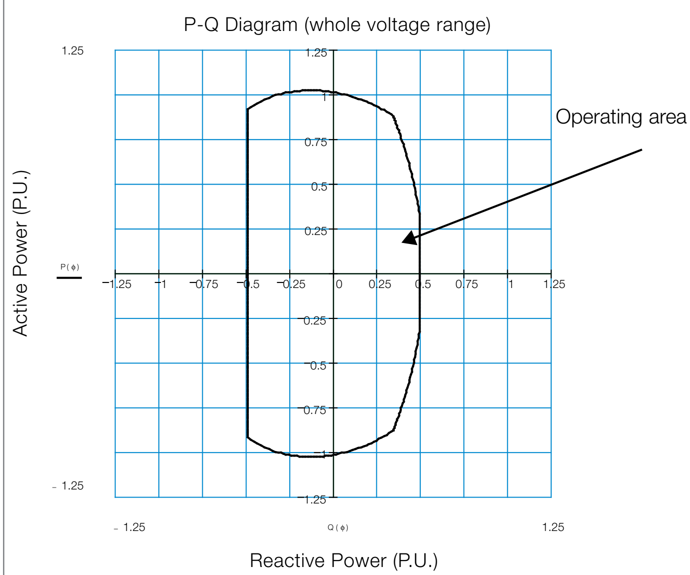

HVDC Classic

- Thyristor used as active component in valves
- Single silicon wafer
- Both forward and reverse blocking capability
- Very high surge current capability
- No gate turn-off; line commutated

Phase angle control

- The thyristor cannot be switched off with a control signal
- It automatically ceases to conduct when the voltage reverses
- Line commutated, 50/60 Hz

1 Simplified single-line diagram for HVDC Classic I 2 Mass impregnated HVDC cable I 3 Reactive power exchange for HVDC Classic.

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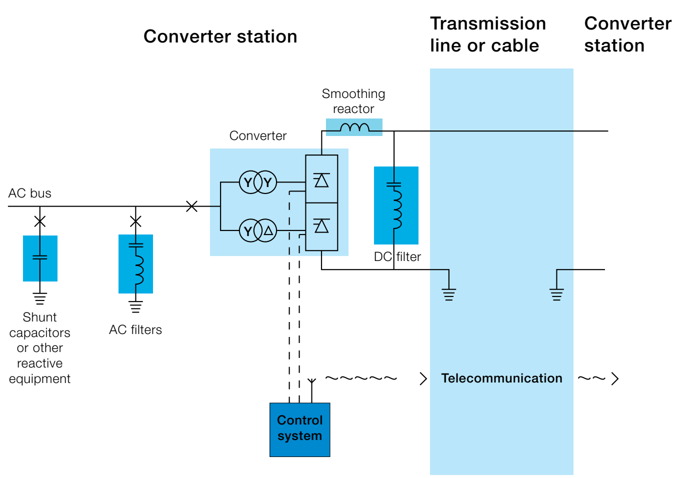

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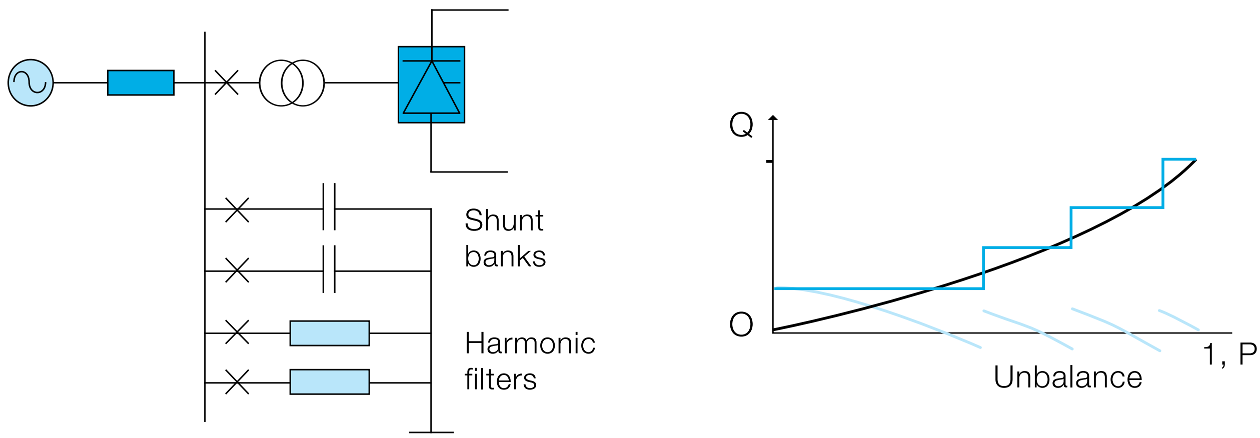
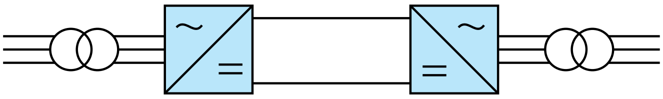


2.18 Operating configurations

HVDC/HVDC Light® converters can form a transmission system in various operating configurations. The most common operating configurations are briefly described below highlighting the main advantages/disadvantages:

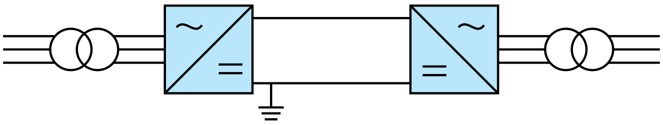
Symmetric monopole



Advantages:
- No infeed of fault currents from the AC grid at DC pole ground faults
- Transformers are not exposed to DC stresses
- No DC ground current

Disadvantages:
- Limited redundancy compared to a bipolar configuration
- Requires two fully insulated DC conductors

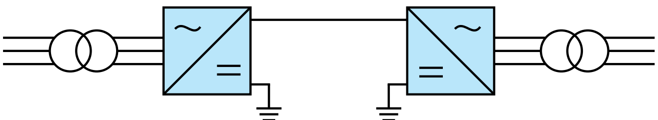
Asymmetric monopole, Metallic return



Advantages:
- The metallic return DC conductor does not require full insulation
- Allows for expansion to a bipolar system at a later stage
- No DC ground current

Disadvantages:
- Limited redundancy compared to a bipolar configuration
- Transformers must be designed for DC stresses

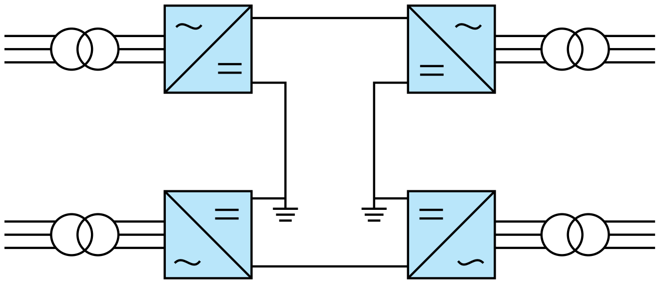
Asymmetric monopole, Ground return



Advantages:
- Cost and losses are minimized due to the single DC conductor
- Allows for expansion to a bipolar system at a later stage

Disadvantages:
- Requires permission for continuous operation with DC ground current
- Requires permission for electrodes (including environmental effects)
- Infeed of fault current from the AC grid at DC pole ground faults
- Limited redundancy compared to a bipolar configuration
- Transformers must be designed for DC stresses

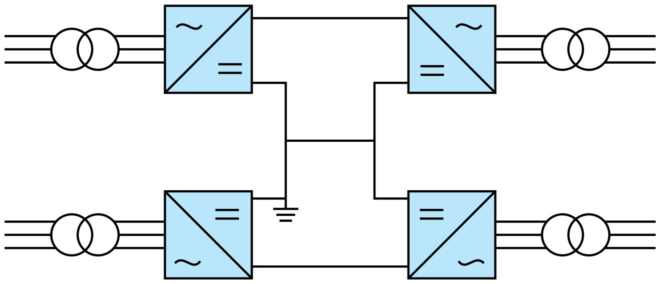
Bipole, Ground electrodes



Advantages:
- Redundancy for 50 percent of the total rating

Disadvantages:
- More costly for the same rating compared to monopolar configurations
- Requires permission for temporary operation with DC ground current
- Requires permission for electrodes (including environmental effects)
- Infeed of fault current from the AC grid at DC pole-ground faults
- Transformers must be designed for DC stresses

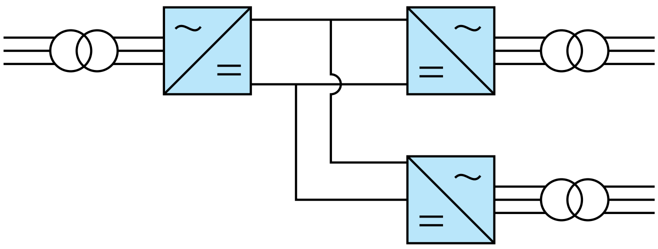
Bipole, Metallic neutral



Advantages:
- Redundancy for 50 percent of the total rating

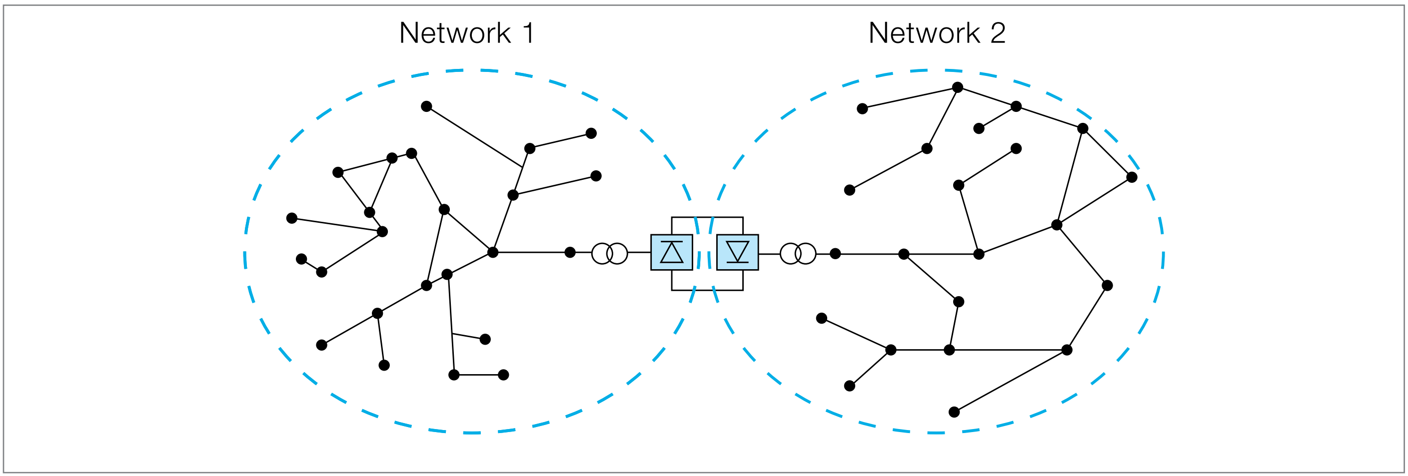
Disadvantages:
- More costly for the same rating compared to monopolar configurations
- Requires low-voltage insulated DC neutral conductor
- Transformers must be designed for DC stresses

Multi-terminal



Multi-terminal systems can be constructed based on all described configurations. A three-terminal example, based on symmetric monopoles, can be seen above.

Back-to-back stations connect asynchronous networks.



2.18.1 Back-to-back

A back-to-back station consists of two HVDC Light® converters located close to each other, i.e. with no DC cables in between.

A HVDC back-to-back station is normally used to create an asynchronous interconnection between two AC networks. There are several back-to-back stations in operation in the world. In these installations both the rectifier and the inverter are located in the same station and are normally used in order to create an asynchronous interconnection between two AC networks, which could have the same or different frequencies.

A back-to-back station is normally somewhat simpler than a converter station for a transmission project. The direct voltage level can be selected without consideration of the optimum values for an overhead line and a cable, and is therefore normally quite low, 150 kilovolts (kV) or lower. The only major equipment on the DC side is a smoothing reactor. The control equipment can also be simplified, as there is no need for a telecommunication link between the two converters.

2.18.2 HVDC grid

HVDC grids is an important step towards an energy system based on renewable energy sources. The growing need to integrate and transmit large amounts of remote renewable energy and to interconnect different power markets is a driving force for growth of HVDC transmission systems. With the increasing number of DC systems being installed, a larger overall DC transmission system – an HVDC grid – could emerge. Such a DC grid could act as an overlay or backbone system integrated with the existing AC grid, where several DC terminals are serving multiple purposes.

2.19 Drivers for choosing an HVDC Light® application

AC network support

- Active and reactive power independently and rapidly controlled
- Operation down to short-circuit ratios of zero
- Loop flows of power are avoided
- Black start is possible
- Stabilization of connected AC grids
- Share spinning reserve between areas
- Continuously variable power from full power in one direction to full power in reverse
- Emergency power support
- Increase power in parallel AC lines
- No commutation failures
- Multi-terminal system simple
- No minimum power - can operate down to zero power
- Additional reactive shunt compensation is not required (only small harmonic filters are needed)
- Only conventional AC transformers are required
- The HVDC Light® control can be designed so that the HVDC Light® stations can eliminate flicker and selected harmonics in the AC grid
- The HVDC Light® stations can be operated as STATCOMs, even if they are not connected to a DC line. It is possible to build one or two stations for voltage stabilization and connect them later with cables to create an interconnection.

Undergrounding by cables

- No visible impact of overhead lines; underground cables instead
- Easier to get permission to install
- No relevant electromagnetic fields
- No audible noise, unlike overhead lines

Required site area for converters

- Less space per MW required than for conventional HVDC
- Indoor design - reduced risk of flashover
- Small space requirement and low weight are very important for offshore applications

Environmentally sound

- Audible sound reduced by indoor design
- Stations look like any ordinary industrial building, no outdoor switchyards
- Low building height
- Bipolar operation – no need for electrodes

Energy trading

- Fast and accurate power control – you get the power you want
- No filter switching at power change
- Smooth power reversal (step less power transfer around zero MW)

3 Applications

With the features presented in the previous chapter, HVDC Light® is the preferred system for use in a variety of transmission applications, using submarine cables, land cables, overhead lines or connected back-to-back.

3.1 Connecting remote offshore wind

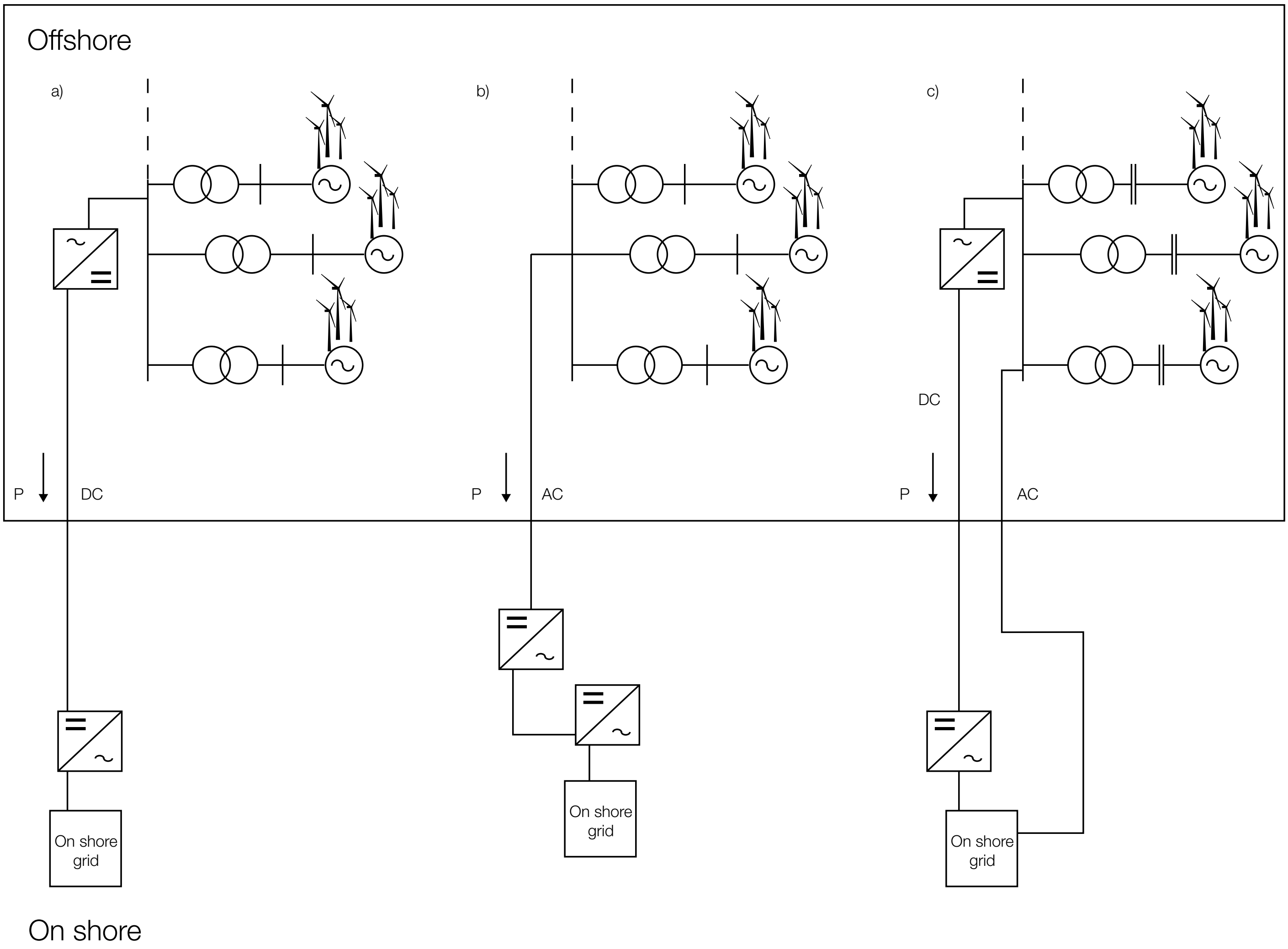
Offshore wind power generation is becoming a key source of large-scale renewable energy supply, and makes a vital contribution towards efforts to lower the environmental impact of electrical power generation.
In many countries, the best onshore locations for wind parks have already been developed, so utilities and energy sector developers are turning to offshore sites. The main attraction of going offshore is the enormous wind resource available. Average wind speeds offshore can be 20 percent higher, and the resulting energy yield up to 70 percent greater than on land. The lack of obstacles such as hills, trees and the smooth surface of the sea also make the wind offshore more reliable. As more and larger wind parks are planned for offshore locations, it is necessary to find ways of reliably and efficiently feeding the power generated back into the AC grid.
This is now both technically and commercially feasible. Large offshore wind parks can be connected to mainland power grids with either HVAC or HVDC transmission systems. Depending on the size of the park and grid conditions, HVDC is needed where the distance to the mainland grid exceeds the range of 50-100 km. Projects such as this need a robust electrical transmission system that can ensure high availability and minimal maintenance requirements. In addition, these systems must adhere to strict national grid codes, and must be able to withstand the harsh and sometimes ferocious offshore climate conditions.

Essential points

- The impact of large-scale offshore wind power generation on power system performance requires special attention, since coastal connection points are often relatively weak. The power connection between the offshore park and the mainland grid must strictly follow all applicable connection regulations, or grid codes, to protect the stability of the grid. Such grid code compliance is met easier with an HVDC system. The HVDC system also helps to manage power quality onshore. It can quickly compensate for fluctuations in power levels, making it the ideal technology for stabilizing irregular electricity flows, such as those generated by wind farms. The technology also supports weak grids with black start capability, fine control of AC voltage and reactive power, as well as the ability to energize wind parks at low wind speeds.

Offshore wind parks are becoming a key source of energy supply.

Three basic transmission types for an offshore wind park.



– Another issue to be considered is the fault ride-through capability in case of AC grid faults. The HVDC technology allows the wind park to decouple, or “immunize” itself against electrical disturbances on the mainland grid if necessary, protecting turbines and equipment. The DC system evacuates the surplus energy from the wind park during AC network faults. No abrupt change in the output power from the wind turbines will occur, and the disturbance to the wind turbines is minimized.
– An HVDC Light® converter station provides fast, effective voltage control during the start-up of an offshore network. Voltage is ramped up smoothly at rated frequency to prevent transient over-voltages and inrush currents. Finally, the wind turbine generators are connected to the offshore network, a functionality that is only possible with an HVDC Light® converter.
– Environmental restrictions on overhead power lines and substations in coastal areas are common, thus making the option of undersea and underground oil-free cables combined with an HVDC converter station with a small footprint and reduced visibility attractive.
– The HVDC Light® system developed by ABB for offshore connections can safely and reliably integrate large-scale wind power production. The system has low losses and stations with small footprint and light weight, which is important when placing them on offshore platforms.

Figure 1 shows three basic transmission types for an offshore wind park. Power levels from around 100 MW to about 1,200 MW are possible with one circuit.

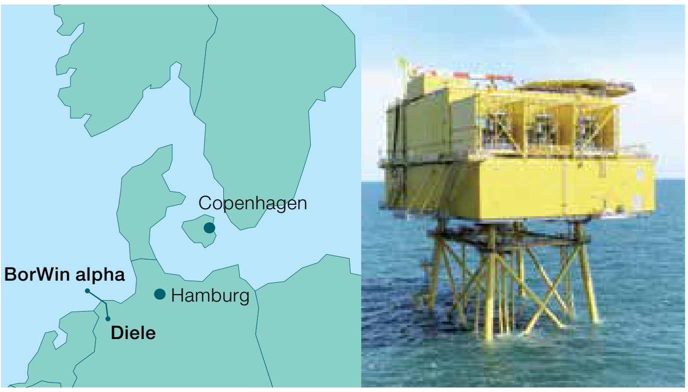
a) The wind park connected directly to the shore by HVDC Light®;
b) An HVDC Light® back-to-back solution;
c) A parallel case with AC and HVDC Light®

The direct connection solution (a) and the back-to-back solution (b) have the advantage of being able to use a variable frequency in the wind park. The wind park is also isolated from electrical disturbances in the shore grid. Significant “fault ride-through” capability is achieved. The parallel case to the right (c) has the benefit of building transmission capacity in steps.

3.1.1 Reference projects

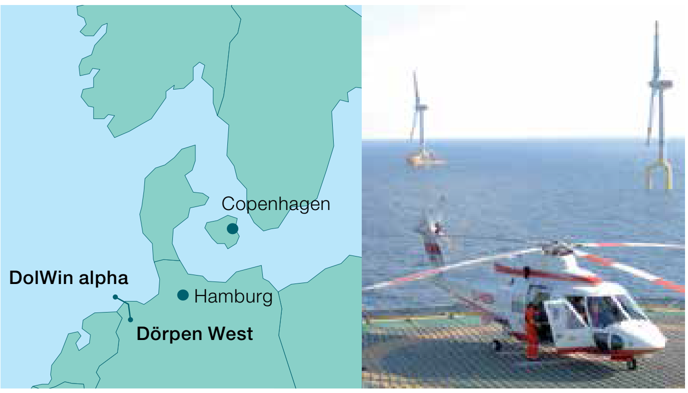
BorWin1 is the name given to the grid connection of BARD Offshore 1, one of the world's largest and most remote offshore wind farms, located in the North Sea. ABB technology will integrate the power generated here into the German mainland grid with a 400 MW HVDC Light® transmission system, which includes an offshore and onshore converter station and cable, 75 km underground and 125 km submarine. Full grid code compliance ensures a robust network connection. The completed BARD Offshore 1 wind farm will consist of 80 wind turbines rated at 5 MW each. These will feed the receiving station at Diele on the German mainland, where the wind-generated power will be injected into the German 380 kV grid. This project will reduce CO_2 emissions by nearly 1.5 million metric tons per year, replacing fossil-fuel generation. The transmission system also supports further wind power development in Germany.

BorWin1.



Another example of this type of solution is the 800 MW ±320 kV DolWin1 HVDC Light® transmission using 75 km of DC sea cable and 90 km of land cable in the same area, which brings power to the grid connection point at Dörpen West, Germany. ABB is responsible for system engineering including design, supply and installation of the offshore converter and its platform, sea and land cable systems as well as the onshore converter station. Scheduled to be operational in 2013, the offshore wind farms belonging to the DolWin cluster expected to avoid 3 million metric tons of CO_2 emissions per year by replacing fossil-fuel based generation.

DolWin1.



3.2 Power-from-shore

Traditionally, offshore platforms generate their own electricity by burning fossil fuels to run onboard gas turbines and/or diesel-powered generating units. This method is inefficient and has come under increasing scrutiny and criticism because it creates substantial greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), consumes large amounts of fuel, and adversely impacts the health and safety situation of platform workers. Some regions also put a high tax on CO_2 emissions, adding to the already steep operating costs of platform generating systems. These and other factors, such as strong public opposition to increasing greenhouse gas emissions, mean the offshore industry must start searching for other ways to provide platforms with electrical power.

One alternative is to supply offshore installations with electricity from the mainland using a power cable transmission system. By replacing costly and bulky onboard electrical generating systems, a power-from-shore solution can eliminate platform CO_2 emissions entirely. It also increases available space, reduces weight on the platform, and improves the working environment. In addition, cable systems are easier to maintain than rotating generators.

ABB's HVDC Light® power-from-shore system is a proven technology that provides significant benefits to customers who need reliable power in remote places.

Essential points

- The offshore industry's main requirement of any power supply solution is high availability, since an emergency shutdown means loss of production capacity and profit. Environmental impact, weight and size are other important issues and last but not least, the health and safety environment of platform workers must never be compromised.
- Until recently, power-from-shore solutions were limited to AC cable systems over short distances in the range of 50-100 km. The introduction of voltage source converter (VSC) technology in the late 1990s opened up the market segment, because VSC technology makes it cost effective to supply large amounts of power over long distances using robust, lightweight, oil-free cables.
- VSC technology does not need any short circuit power to operate, which makes it an ideal technology to start up and energize offshore platforms. A VSC system allows for fully independent control of both active and reactive power. The technology ensures smooth energization and startup, as well as precise control of the platform's power system.
- Maintenance is minimal, simple, remote and safe, which reduces the need for offshore staffing compared to gas turbines which require the constant presence of maintenance crews.
- From a health and safety perspective, power-from-shore eliminates all hazards associated with gas-fired rotating equipment operating in vicinity of platform workers. The reduced noise levels and vibrations, are also important workplace improvements.
- Furthermore, power-from-shore solutions produce no emissions, so there is no emissions tax to collect.
- The small and compact solution facilitates the assembly, with short installation and commissioning time as consequence. It also means less weight and volume on the platform than traditional solutions.
- The lifetime of a DC installation is typically 30-40 years, which is very high compared to local generation offshore.

3.2.1 Reference projects

The Troll A precompression project delivered to Statoil and commissioned by ABB in 2005 was the first HVDC Light® transmission system ever installed in an offshore platform. It is located in the Troll oil and gas field in the North Sea, about 65 kilometers west of Kollsnes, near Bergen, Norway. This field contains about 40 percent of total gas reserves on the Norwegian continental shelf, and is the cornerstone of Norway's offshore gas production.

The ground-breaking solution delivers 88 MW of power from the Norwegian mainland to power a high-voltage variable speed synchronous machine installed on the platform to drive compressors that maintain gas delivery pressure, compensating for falling reservoir pressure.

The system eliminates GHG emissions from the Troll A platform. This solution was selected because of its positive environmental effects, the long cable distance under water, and the compactness of the converter on the platform.

In 2011, ABB was awarded a second power-from-shore contract from Statoil for the Troll A platform, this time to provide 100 MW to power two additional compressor drive systems. It is scheduled to go into operation in 2015.

The Troll A 3 & 4 pre-compression project scope of supply includes two compressor drive systems rated at 50 MW each, consisting of one high-voltage motor and high-voltage direct current (HVDC) power transmission system, including HVDC converters and subsea direct current cables. After installation and commissioning in 2015, all four trains will provide in total about 144 MW of power. All trains are independent of each other, and can be driven separately, with different loads. This provides great operational flexibility and very good reliability as a result of redundant systems.

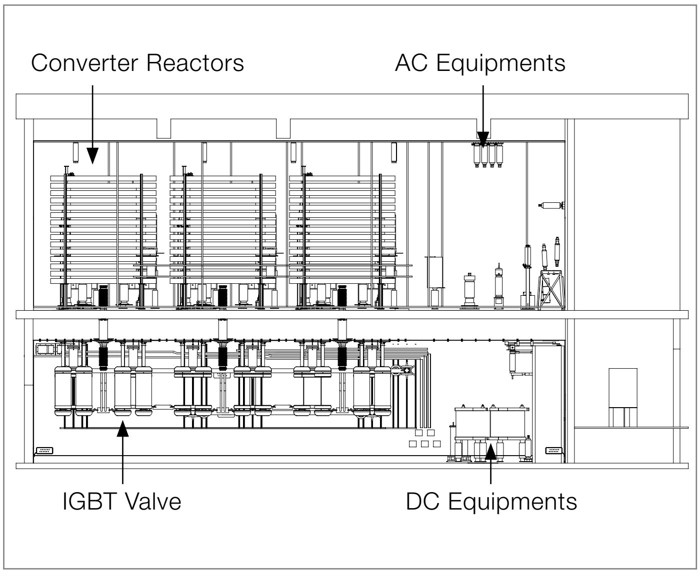
The Valhall HVDC Light® power-from-shore transmission system was commissioned in October 2011, and replaces gas turbines on BP's linked multi-platform complex in the North Sea, about 294 km from the Norwegian mainland. This VSC power cable system delivers 78 MW to run the offshore oil and gas field facilities.

The project is part of a redevelopment scheme to increase production at the 30-year-old complex and equip it for another 40 years of service. Improvements include a new production and hotel platform that require more electric power than is currently available. ABB is responsible for the system engineering and the design, and is supplying the VSC system.

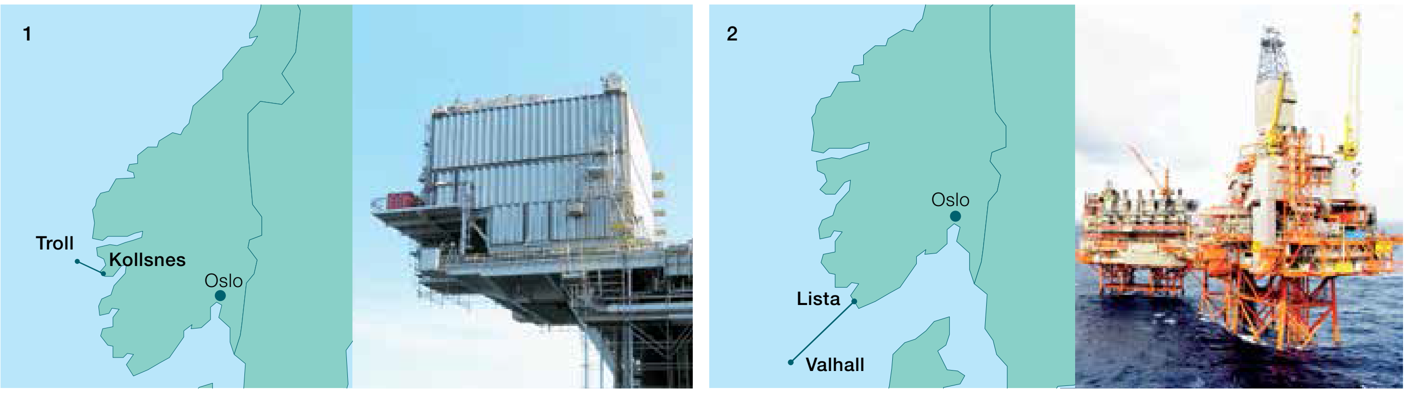
According to BP's own estimates, the considerable benefits to be gained from ABB's HVDC Light® power-from-shore technology versus conventional gas turbine generators include:
- significantly lower operating and maintenance costs
- elimination of 300,000 tons of CO_2 and 250 tons of NOX emissions a year
- avoidance of emissions tax
- improved working environment

BP points out that there is minimal risk of fire and explosion as well as less noise and vibration after installing the HVDC converter module on the platform. Maintenance is minimal, simple, remote and safe, which reduces the need for offshore staffing compared to gas turbines which require the constant presence of maintenance crews.

Troll A 3 & 4.



1 Troll A | 2 Valhall.



3.3 Connecting remote loads

Electrical systems are mostly built as meshed networks with multiple interconnections between various loads and generation stations. In such a network, the power can be exchanged over different routes, and the cost of power can be considered common to all loads in the network. However, there are also many hard-to-reach places that are not connected to a power network at all today.

These distant loads include islands and cities in remote areas, or industries in remote locations such as mines. The supply of power to a distant load can be made by a radial transmission from a meshed network or by local generation using, for instance, diesel generators or gas turbines. Depending on the amount of electricity needed, the distance from the grid to the load and other geographical factors, DC transmission can complement or replace local generation as the power supply for a remote load.

Essential points

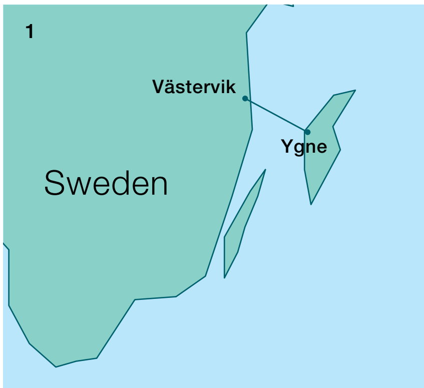
- HVDC is a proven electrical transmission system for remote loads that can eliminate polluting, inefficient and expensive local generation, and provide remote, off-the-grid locations with reliable, environmentally friendly power supplies. If the remote load is located in a tourist or otherwise sensitive area, there are reasons other than strict economics to consider a transmission alternative.
- Fees on pollution and carbon dioxide emissions from diesel generators or gas turbines may also make HVDC transmission solutions more competitive and attractive.
- As a by-product of DC transmission a fiber optic cable could easily be attached to the same infrastructure when laying the cable or installing the transmission line, thus improving the quality of life for the population in the remote location.
- A transmission link also makes sense if local renewable generation such as hydro, solar or wind power exists or is planned, because the surplus energy produced can easily be exported and the back-bone AC network supported as needed.
- In the case of sea crossings to islands and peninsulas, AC cables are only feasible for relatively short distances, in the range of 50-100 km. An HVDC Light® system has no distance limitation.
- The HVDC link can be designed for maintenance kept to a minimum and performed during short biannual periods.
- Self-commutation, dynamic voltage control, and black-start capability allow compact HVDC Light® transmission to serve isolated loads long-distance underground or submarine cables. HVDC Light® technology can operate at variable frequency to more efficiently drive large compressor or pumping loads using high-voltage motors, making it a viable power alternative for industrial sites.

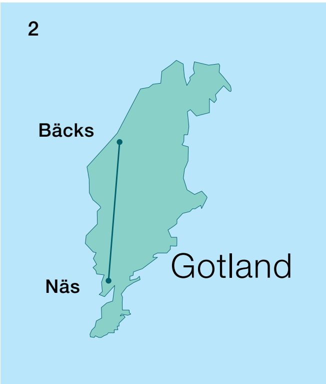
3.3.1 Reference projects

The original Gotland sea cable transmission is a 260 MW bipolar HVDC Classic cable transmission from Västervik on mainland Sweden to Ygne on the island of Gotland. It was built in 1954 and expanded in 1983 and 1987. The main reason for choosing HVDC transmission was to replace local generation on the island with a more environmentally friendly system, and also due to the considerable length of the sea crossing from the mainland, 96 km.

In 1999 a 50 MW HVDC Light® underground cable transmission was installed from the southern tip of the island in Näs to Bäcks close to the classic HVDC station in Ygne. Wind farms had been installed in the south of the island, and this new renewable energy generation needed to be evacuated. HVDC Light®'s capacity to overcome the power quality problems in wind power plants and the possibility of transmitting the power via underground cables also encouraged the local utility, GEAB, to install the system. All equipment was mounted in enclosed modules in the factory and were fully factory tested, so that civil works, installation and commissioning was kept to a minimum.

1 HVDC Classic link from 1954 | 2 HVDC Light link from 1999.



3.4 Interconnections

Liberalized energy markets have introduced new concepts to electricity sectors in many regions of the world.

In Europe for instance the energy policy, in which the goal is to create a secure, sustainable and competitive energy supply for all European citizens and companies, will be implemented by encouraging the integration of dozens of electricity networks across the continent, expanding trade and competition within the European Union's electricity markets.

The EU hopes that expanding the continent's limited cross-border capacity for electricity exchange will help to balance electricity prices and enable the most efficient use of power generation assets, helping to create a secure, transparent, harmonized and competitive electricity market.

Another reason for interconnecting AC networks with HVDC is its ability to control the systems in an efficient way and to act as a "fuse" against propagating disturbances which recently have caused major problems in networks in different parts of the world, e.g. the Northeastern U.S. and parts of Europe.

HVDC is the only possible technical solution when interconnecting energy markets that operate at different frequencies (asynchronous), or are otherwise incompatible. They are used for interconnecting national grids of two or more countries or to strengthen the power system within a country.

Essential points

- HVDC interconnections contribute to the overall reliability and security of each connected system, help reduce system losses, increase transmission capacity, and improve power quality in the adjacent AC network.
- The inherent controllability of HVDC Light® systems becomes more and more important for network operators, especially with the integration of renewable energy into the energy mix, which has different characteristics compared to a traditional fossil fuel based energy matrix.
- Power in an HVDC transmission system can flow in both directions and be precisely controlled. This means that demand and supply can be balanced effectively, which facilitates power trading.
- Interconnections are used for stabilizing and controlling transmission networks in order to prevent cascading outages that have occurred in Europe and the U.S. in recent years.
- DC is the only option for the underground and underwater transmission of power over distances in the range of 50-100 kilometers.
- Interconnecting two systems with HVDC creates a technical/economical advantage in that spinning reserve capacity necessary for system stability in each network can be shared, so that if one suffers from a disturbance, it can borrow spinning reserve from the other system, and vice versa. This can postpone, or even eliminate the need for investments in new generation in both networks.
- A specific and commonly used type of asynchronous interconnection can be made with a so called back-to-back station, which consists of a DC link with both the sending and receiving station located within the same substation. Back-to-back stations don't require any transmission line and are a simple, fast and cost-effective way to couple electricity markets. In most cases, permit times are greatly reduced.
- A black-start capability can be implemented which can be beneficial in order to speed up grid restoration in the unlikely event of a blackout.

3.4.1 Reference project

The 500 MW East-West Interconnector HVDC Light® transmission system will connect the grids of Ireland and Wales. This is the first HVDC Light project to use ±200 kV cables and the link is about 260 km long.

Ireland has plans to expand the wind power generation and the link will facilitate addition of renewables and give the possibility to export excess energy to the UK market and vice versa. The new link will also enchance security of supply in the Irish grid and allow Ireland and Britain access to more competition.

East-West Interconnector.

3.5 DC links in AC grids

Modern power grids need enhanced and flexible ways of controlling the flow of electricity within their networks, because it is a challenge to increase transmission capacity and flexibility with conventional AC expansion options, especially in meshed and heavily loaded networks.

The demand for reliable supplies of electricity is growing, increasing the need for more intelligent, high-level system control of power networks. Network congestion is increasing in many regions around the globe. Furthermore, the coupling of previously separated electricity markets and growing commercial interconnections require precise, controllable power flows in order to operate effectively.

In power transmission investments, features such as power quality improvement, stability enhancement, frequency and voltage regulation, emergency power support, bottleneck mitigation and controllability of power flow are often considered "nice-to-haves," but otherwise are not usually given sufficient attention in the investment assessment unless they are deemed absolutely essential from a purely technical point of view.

Today, however, such features are becoming more and more important for network operators especially with the integration of renewable energy, which has different characteristics compared to a traditional fossil fuel based energy matrix. These need to be addressed when considering the various alternatives of a power transmission investment.

Essential points

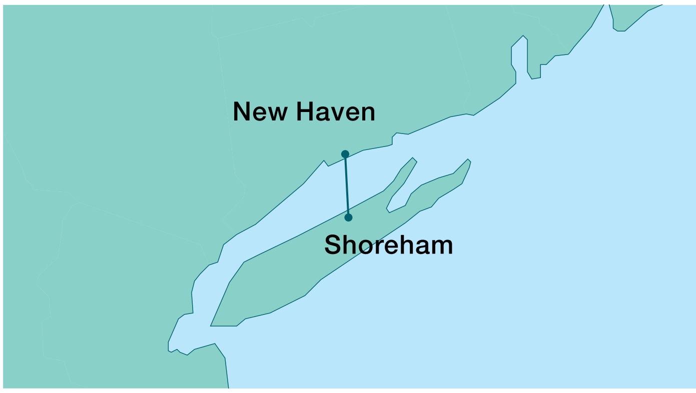
- An increasing number of HVDC transmission systems embedded in the AC grid will result in a more controllable and precise power exchange. HVDC links may be used to control power flow in the AC network, thus optimizing and increasing the transmission capacity through the existing lines and at the same time reducing the overall losses.
- Reducing bottlenecks in heavily loaded AC networks is one of the effects achieved by installing a DC link inside an AC grid. HVDC VSC technology can be used as a traditional HVDC link carrying power from one point to another. Because of its capacity to inject reactive power into the adjacent AC network, it not only increases transmission power by its own power ratings, it also increases the power transmission capability in the adjacent AC network. Examples exist where the total transmission capacity increases by 150 percent with the introduction of a VSC link at 100 percent transmission capacity.
- An HVDC link inside an AC network can be used to strengthen a weak point in the power system at the same time it increases power transmission capacity and gives the operator increased controllability and flexibility over the network and power flow.

3.6 City center infeed

Power loads in cities are increasing as the world urbanizes, and metropolitan power networks are continuously upgrading in order to meet the demand for power. At the same time, environmental issues are at the top of the global agenda, as powerful forces push to replace old-style local generation with power transmission from cleaner sources.

Land space being scarce and expensive, substantial difficulties arise whenever new right-of-way must be secured to carry additional power over traditional transmission lines. As power transmission levels increase, the risk of exceeding the short-circuit capability of existing switchgear equipment as well as other network components becomes another real threat to the expansion of power networks. The effect of increasing demand on the power quality in urban areas is also an important factor to consider for the power system engineer.

Cross Sound Cable.



Strategies to develop urban power networks must address issues like power congestion, pollution, acoustical and electrical noise, power quality and control, short-circuit power restriction, permits and the scarcity of land for sites, among other factors. Faced with steep increases in demand, urban electrical systems require solutions that may be easily located within urban boundaries, and have short lead times from decision to transmission.

Essential points

- The problems mentioned above can be efficiently solved with ABB's HVDC Light® transmission system, featuring VSC-based technology and oil-free DC transmission cables. This system uses small power stations ideal for feeding electricity with low losses into densely populated urban centers. It is quick to build and commission thanks to its modular, pre-assembled design. Power is transmitted via extruded polymer underground cables.
- The advanced power control capabilities of an HVDC link can be used to control the power flow in the AC network, thus optimizing the load flow through the existing lines and in turn helping to reduce overall losses in the grid, increase capacity and improve stability.
- The permit process for projects using DC underground cables is also normally faster and easier than for traditional overhead AC transmission lines.
- The use of existing waterways, road banks, railroad track banks and overhead line right-of-ways are some possible alternatives for the cable route. DC cable has no technical limit with respect to transmission distance.
- Replacing existing AC overhead lines with DC cables is an opportunity to create a more effective power corridor using the same right-of-way, since DC can transmit 2-to-3 times more power (in some cases even more) than a comparable AC system, without creating stability problems.
- Laying and jointing extruded DC transmission cables can be done quickly, because the cables are robust and flexible. The pre-fabricated joints can be speedily installed, taking considerably less time than conventional cables.
- To reduce visual impact, a major part of an HVDC station or the entire station can be built as an enclosed building to fit into its surroundings. The station design is suitable for handling high power levels on a compact site, which is very useful where real estate is at a premium.

3.6.1 Reference project

Cross Sound Cable is an HVDC Light® underwater cable link between Connecticut and Long Island, New York. ABB has provided a complete 330 MW, 40 km HVDC Light® transmission system. The system is made up of high-tech extruded, oil-free, cables buried under the seabed, with a converter station at New Haven, Connecticut and Shoreham on Long Island.

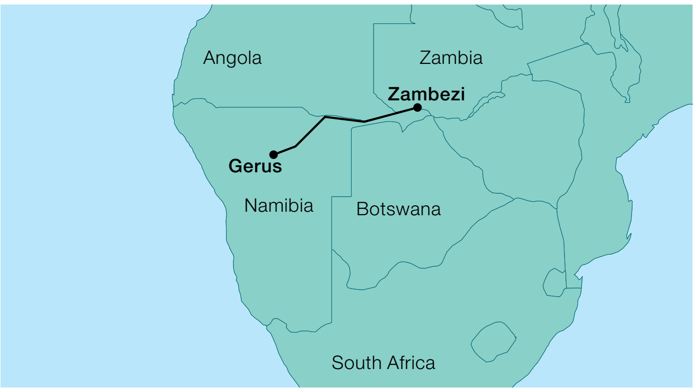
The Cross Sound Cable improves the reliability of power supply in the Connecticut and New England power grids, while providing urgently needed electricity to Long Island. The HVDC Light® connection is also designed to promote competition in the New York and New England electricity markets by enabling electricity to be traded among power generators and customers in both regions.

The Cross Sound Cable HVDC Light® link has proven itself to be a very valuable asset during grid restoration efforts following the large blackout of August 14, 2003 in the USA, and was the first transmission link to Long Island to go back into service. HVDC Light® transmission will be available almost instantly after a blackout, and does not need any short circuit capacity (black start capability) to become connected to the grid.

3.7 Connecting remote generation

The world's demand for energy continues to grow at a rapid pace. Today, energy is mostly generated by burning fossil fuels, but in addition to the serious impact this has on the environment, fossil fuel resources are finite. As they become harder to find and harvest, sustainable emissions-free renewable energy generation will undoubtedly come to play an important role in the energy business. Getting the power to consumers is an additional challenge, because the best generating sites are often in remote areas, so electricity must often cross vast distances to get to where it is needed most. HVDC is the most reliable and efficient way of getting it there, and HVDC transmission systems are already delivering electricity to millions of consumers every day. For example, a 2,000-km long HVDC transmission line at 800 kV loses about 5 percent of its power to heat, while the power losses in an AC line of similar voltage are around twice as high. HVDC transmission lines also have negligible electromagnetic fields, and require a much smaller transmission corridor than AC systems.

Caprivi Link Interconnector.



It has been argued that comprehensive, interconnected installations of renewable energy such as wind power, solar panels and hydroelectric dams, in combination with some type of storage capacity, can in the future provide all the electricity needed on earth. For such a scenario to actually become a reality, a new kind of overlaying transmission system backbone with high controllability, capacity and efficiency is required. This backbone can benefit from the features inherent in HVDC technology, and HVDC is probably the only technically and economically reasonable solution to the challenge of permanently integrating renewable energy into our present transmission system, and elevating it to the top of our energy mix.

Essential points

- HVDC technology is a robust electrical transmission system that ensures high availability, minimal maintenance and of course, low losses. HVDC transmission systems offer the most cost-efficient and best technical long-distance transmission solutions. Due to inherent technical advantages such as superior controllability, it also makes integrating volatile renewable generation and stabilizing power networks easier.
- For long transmission distances, losses can be a decisive factor when evaluating different investment alternatives. In general, losses for a long HVDC connection with overhead lines are lower than for an HVAC transmission of comparable rating and length.
- For underwater interconnections, AC cable capability is technically limited to a maximum transmission distance of something in the range of 50-100 km. For longer distances, DC is the only technically reasonable solution.
- An HVDC line is more efficient and has a higher power transmission capacity than an AC line at the same voltage. This means that smaller towers can be used and in many cases you can also avoid a second transmission line. By using an HVDC transmission system for transporting energy, the system will have less visual impact than other solutions.

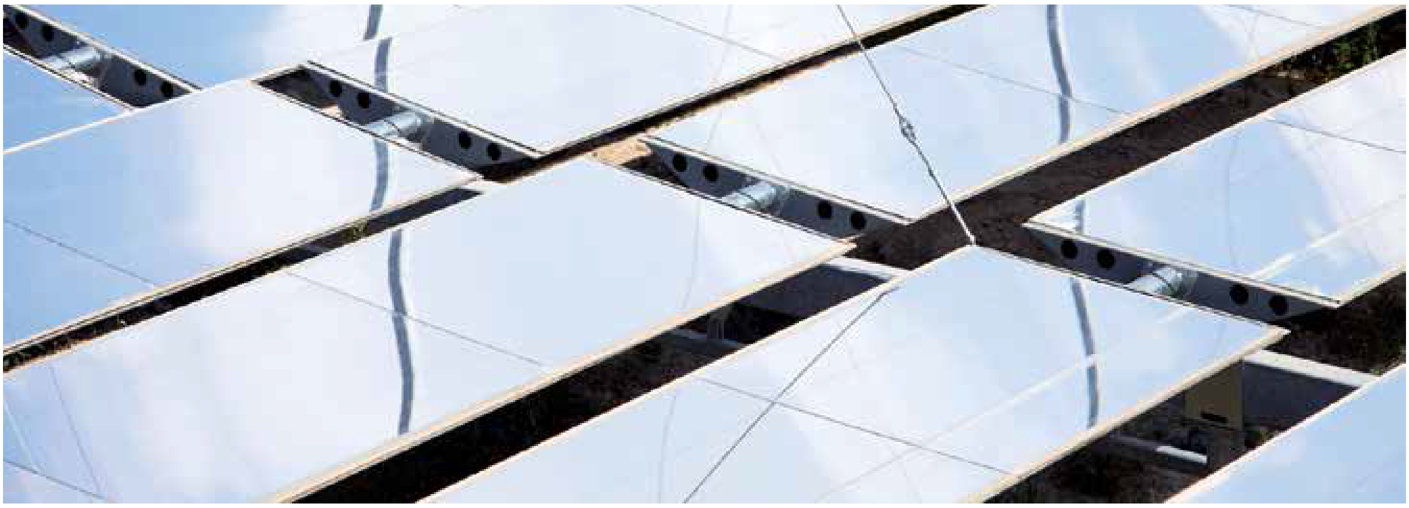
3.7.1 Reference project

The Caprivi Link Interconnector is a 2 x 300 MW interconnection between the Zambezi converter station in the Caprivi strip in Namibia, close to the border of Zambia, and the Gerus converter station, about 300 km north of Windhoek in Namibia. The converter stations are interconnected by a 950 km long, bipolar ±350 kV DC overhead line. This is the first HVDC Light® project to be build with overhead lines.

UHVDC technology with advanced control is particularly suitable for vast countries like China, India and Brazil, where consumption centers are usually far from available power sources. By increasing the voltage level of the transmission, considerable advantages for the environment are gained, such as lower transmission losses and smaller transmission line right-of-ways.

3.7.2 Solar

By using HVDC transmission lines, it will be possible to transport clean power from the deserts over very long distances to the world's centers of consumption. In contrast to conventional AC transmission, HVDC transmission can be installed underground even over long distances, a disappearing act which encourages public acceptance.



4 HVDC Light® technology

4.1 Conceptual design

As for all complex systems, ABB´s selected conceptual design for HVDC Light® is a trade-off between technical performance and cost. Using a solid base of technology modules, developed and refined since the first delivery in 1997, ABB has succeeded in creating a cost efficient converter solution while retaining all of the operational functionalities valued by customers. The design concept is scalable up to the highest transmission voltages, losses are continuously being reduced and reliability is high.

The development of HVDC Light® converter technology has been going over three generations. Generation 1 was a straight forward two-level converter switching the full voltage in a PWM pattern. Generation 2 was a three-level converter where the losses were reduced, but at a cost of more IGBTs. Generation 3 was going back to a two-level converter with reduced number of IGBTs, but keeping the losses down by using optimized switching pattern and more optimized IGBT design.

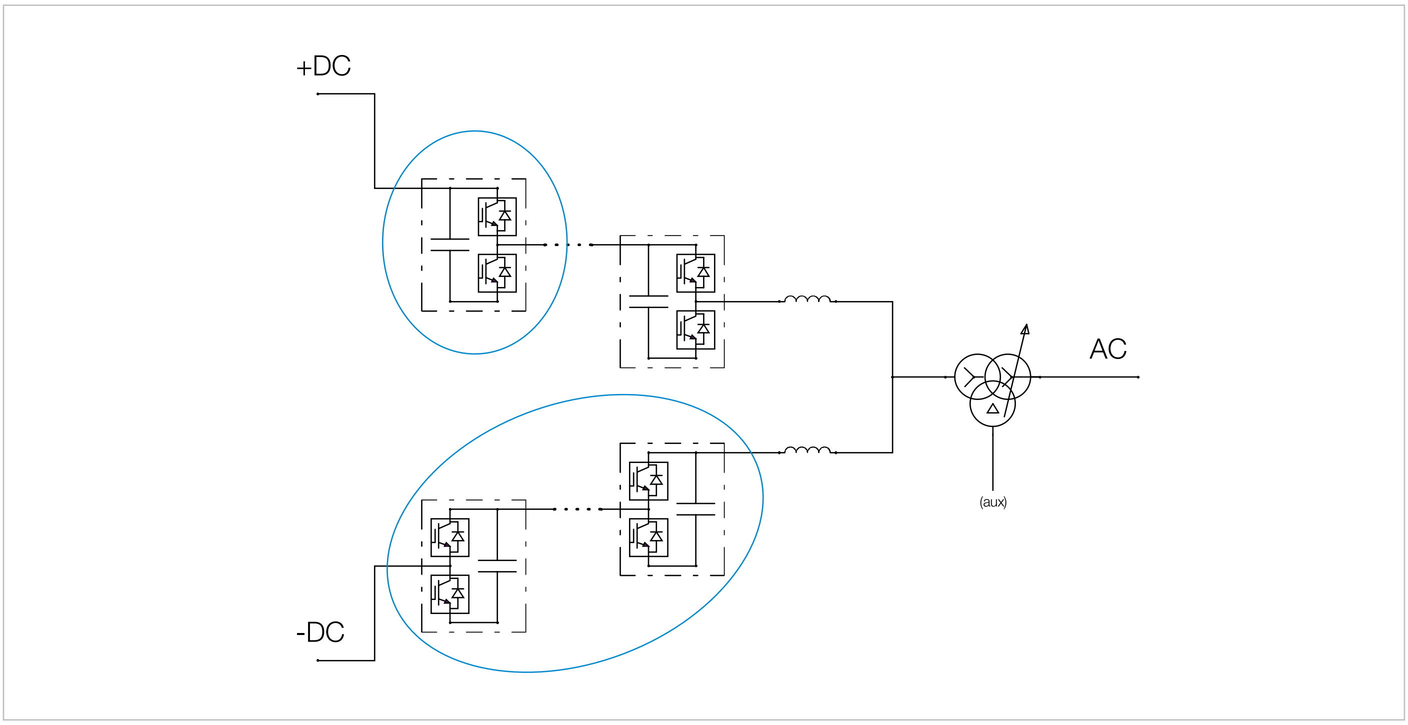
Without the extensive experience gained by ABB during step-by-step development and long term operation over several generations of HVDC Light®, it would not be possible to offer such a well-proven, reliable and optimized converter station design down to the smallest building block.

4.1.1 Generation 4 topology – Cascaded two-level converter

The base module in the most recent converter topology developed by ABB is the two-level converter, used in the previous generations of HVDC Light®. By connecting several smaller two-level building blocks (cells) in series, a Cascaded Two-Level (CTL) converter is obtained. The enhanced two-level converter topology enables the creation of a nearly sinusoidal output voltage from the converter, which in combination with the low switching frequency per cell significantly reduces station losses.

In the CTL converter, the valve becomes the most significant piece of equipment in terms of complexity, space requirement, cost and losses. Based on ABB's operational experience in the previous generations of HVDC Light®, a half-bridge cell configuration has been selected in order to minimize included components and thereby increase reliability. Furthermore, losses and cost will consequently also be decreased.

Simplified circuit diagram of HVDC Light Generation 4 cascaded two-level converter. On the positive arm, a single valve cell is pointed out; in the negative arm, an entire valve arm is highlighted.



4.1.2 Active and reactive power flow

The fundamental base apparent power is defined as follows (See figure 1)

$$S_b = P + jQ = \sqrt{3} * \bar{U}_C * \bar{I}_V^*$$

The active and reactive power components are defined as:

$$P = \frac{U_C \times U_V \times \sin\delta}{\omega L}$$

$$Q = \frac{U_C \times (U_C - U_V) \times \cos\delta}{\omega L}$$

Where:
δ = phase angle between the converter bus voltage UC and the valve bus voltage UV
L = inductance of the converter reactor

Changing the amplitude difference between the converter bus voltage UC and the valve bus voltage UV controls the reactive power flow between the valve and the transformer bus and consequently between the converter and the AC network.

If UV is in phase-lag, the active power flows from AC to DC side (rectifier)
If UV is in phase-lead, the active power flows from DC to AC side (inverter)

If UC > UV, the converter consumes reactive power
If UV > UC, the converter generates reactive power

The typical P/Q diagram, which is valid within the whole steady-state AC network voltage range, is shown in the figure below. The p.u. is related to apparent power (S=P+iQ).

The P/Q diagram shown is for a back-to-back, i.e. with no distance between the sending and the receiving station. The 1st and 2nd quadrants represent the rectifier, and the 3rd and 4th the inverter. A positive value of Q indicates delivery of reactive power to the AC network. It should be noted that the reactive power can be controlled independently in each station.

Typical P/Q diagram. Y-axis: Active power X-axis: Reactive power

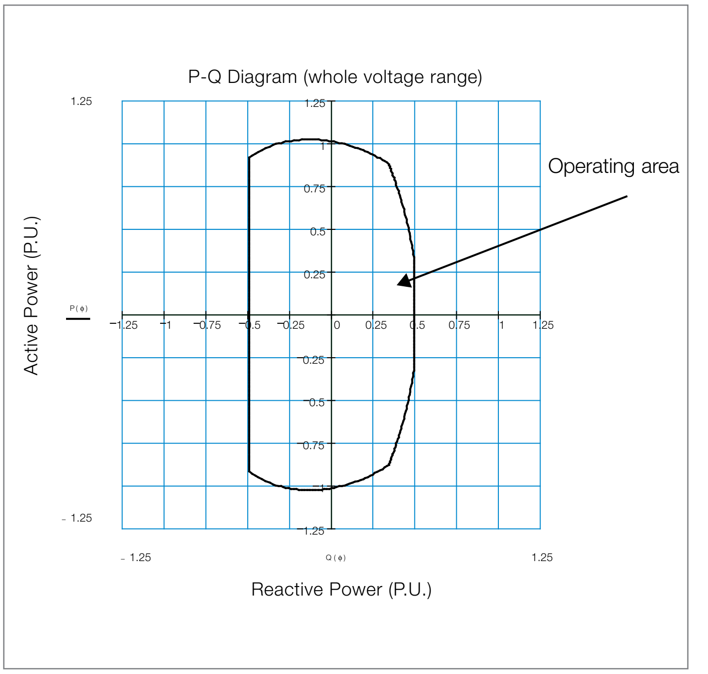
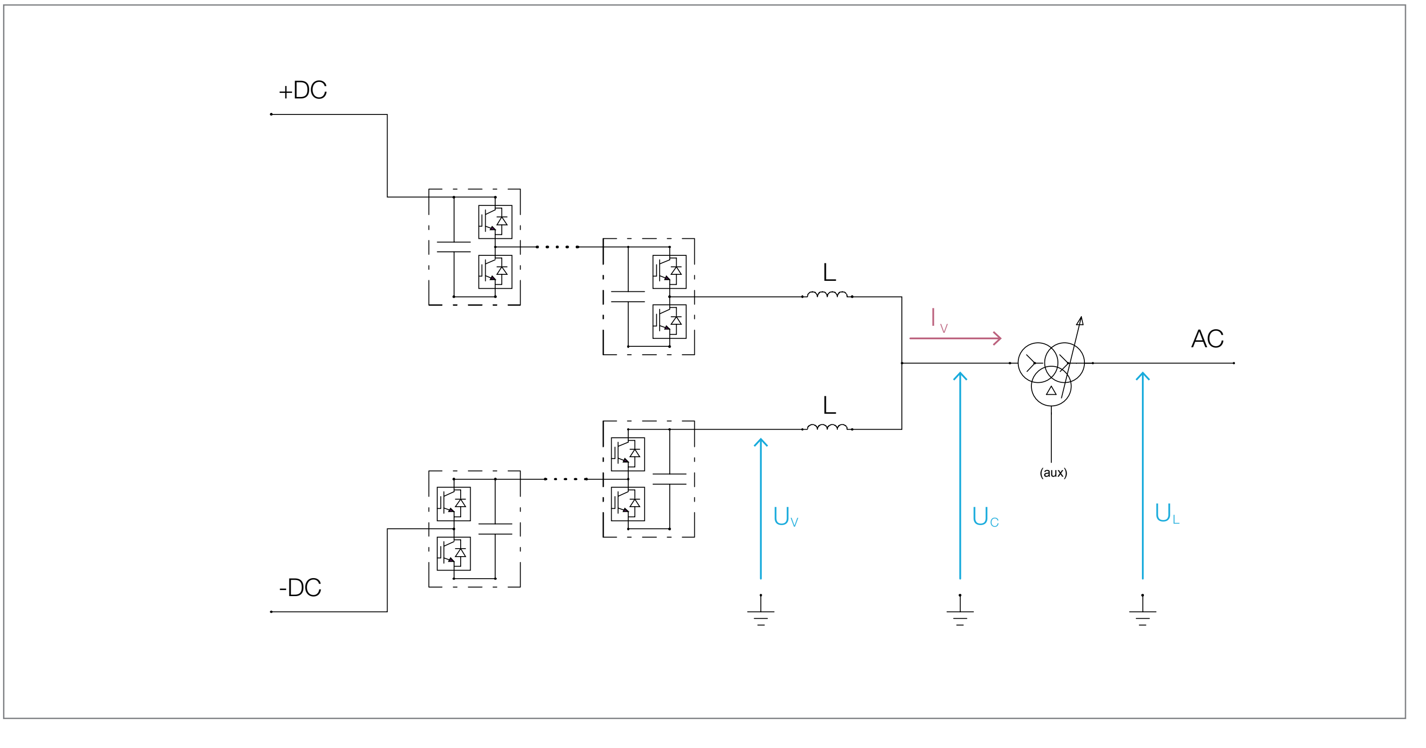


Figure 1 Reactive power flow.



4.2 HVDC Light® base modules

The different HVDC Light® base modules are presented below. The typical power capacity and total losses for different cable lengths are also given for each module. Note that a typical cable size has been chosen for the figures in the tables. The selection of cable size is generally an optimization between the production cost of the cable and the economic evaluation of losses. For example, a larger cross-sectional area results in a more expensive cable, but fewer losses are produced and at a certain cable length, cable life-time and loss evaluation, an optimization point can be found.

HVDC Light® symmetric modules		AC Currents		
		$580A_{AC}$	$1140A_{AC}$	$1740A_{AC}$
DC Voltages	$\pm 80\ kV_{DC}$	M1	M2	M3
	$\pm 150\ kV_{DC}$	M4	M5	M6
	$\pm 320\ kV_{DC}$	M7	M8	M9
	$\pm 500\ kV_{DC}$	M10	M11	M12
	$\pm 640\ kV_{DC}$	M13	M14	M15

4.2.1 ±80 kV symmetric base modules

Symmetric base modules		M1	M2	M3
DC voltage (pole to ground)	kV_{DC}	80	80	80
Base power	MVA	106	209	319
AC current	AC	580	1,140	1,740

Data for ±80 kV symmetric base modules, typical values

Converter	DC voltage	DC current	DC cable	Sending power	Receiving power (MW)					
types	kV	A	Cu in mm²	MW	Back-to-back	50 km	100 km	200 km	400 km	800 km
M1	80	627	300	101.3	99.4	97.0	94.6	-	-	-
M2	80	1,233	1,200	199.2	195.4	193.1	190.8	186.2	-	-
M3	80	1,881	2,400	303.8	301.0	298.1	295.3	292.4	286.8	-

Transfer capability for different cable lengths, typical values for ±80 kV symmetric base modules

Typical layout of an offshore module

The offshore station is designed for compactness, because space and weight capacities are very expensive and scarce on an offshore marine installation. The offshore environment is also very tough and therefore the high-voltage equipment is installed inside a module with a ventilation system designed to protect it and assorted electronics from salt and humid air.

1 Example of a 78 MW land station Lista station, Valhall HVDC Light® link I 2 Approximate weight: 1,280 tonnes, Example of a 78 MW offshore station.

1

2

Typical layout

HVDC Light® 350 MW block

4.2.2 ±150 kV symmetric base modules

Symmetric base modules		M4	M5	M6
DC voltage (pole to ground)	kV_{DC}	150	150	150
Base power	MVA	200	393	600
AC current	AC	580	1,140	1,740

Data for ±150 kV symmetric base modules, typical values

Converter	DC voltage	DC current	DC cable	Sending power	Receiving power (MW)					
types	kV	A	Cu in mm²	MW	Back-to-back	50 km	100 km	200 km	400 km	800 km
M4	150	627	300	189.9	186.3	184.0	181.8	177.3	-	-
M5	150	1,233	1,200	373.4	366.4	364.1	362.0	357.7	349.0	-
M6	150	1,881	2,400	569.7	558.9	556.1	553.3	547.6	536.3	-

Transfer capability for different cable lengths, typical values for ±150 kV symmetric base modules

Typical layout
HVDC Light® 1,000 MW block

4.2.3 ±320 kV symmetric base modules

Symmetric base modules		M7	M8	M9
DC voltage (pole to ground)	kV_{DC}	320	320	320
Base power	MVA	427	839	1,281
AC current	AC	580	1,140	1,740

Data for ±320 kV symmetric base modules, typical values

Converter	DC voltage	DC current	DC cable	Sending power	Receiving power (MW)					
types	kV	A	Cu in mm²	MW	Back-to-back	50 km	100 km	200 km	400 km	800 km
M7	320	627	300	405.1	397.5	395.1	392.7	388.0	379.5	-
M8	320	1,233	1,200	796.6	781.6	777.0	777.0	772.4	764.2	746.7
M9	320	1,881	2,400	1,215.3	1,192.4	1,189.6	1,186.7	1,181.1	1,169.8	1,147.1

Transfer capability for different cable lengths, typical values for ±320 kV symmetric base modules

4.2.4 ±500 kV symmetric base modules

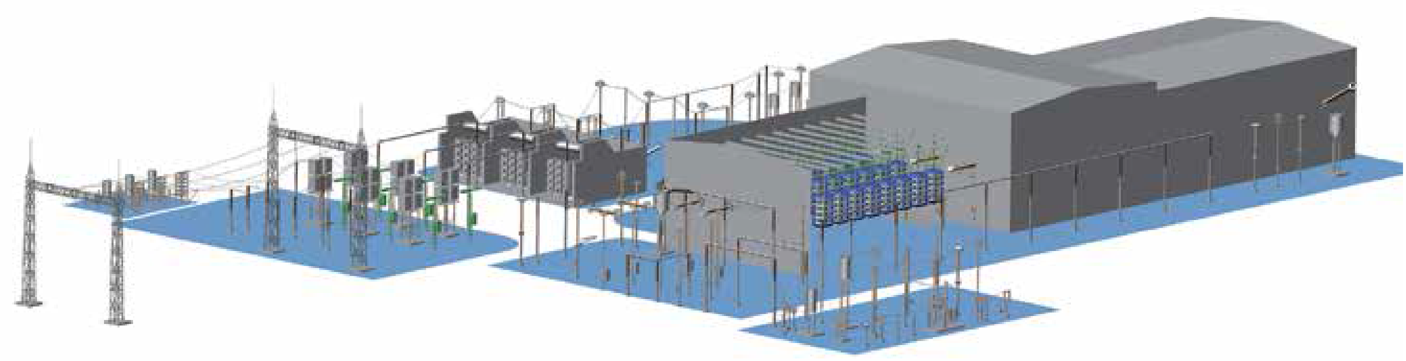
Symmetric base modules		M10	M11	M12
DC voltage (pole to ground)	kV_{DC}	500	500	500
Base power	MVA	667	1,311	2,001
AC current	AC	580	1,140	1,740

Data for ±500 kV symmetric base modules, typical values

Converter	DC voltage	DC current	DC cable	Sending power	Receiving power (MW)						
types	kV	A	Cu in mm²	MW	Back-to-back	50 km	100 km	200 km	400 km	800 km	1,600 km
M10	500	627	300	633.0	621.0	618.7	616.3	611.6	602.1	583.2	-
M11	500	1,233	1,200	1,244.7	1,221.3	1,219.0	1,216.7	1,212.1	1,202.9	1,184.6	1,147.8
M12	500	1,881	2,400	1,898.9	1,863.1	1,860.3	1,857.5	1,851.8	1,840.5	1,817.8	1,772.6

Transfer capability for different cable lengths, typical values for ±500 kV symmetric base modules.

Typical layout HVDC Light® 700 MW block.



4.2.5 ±640 kV symmetric base modules

Symmetric base modules		M13	M14	M15
DC voltage (pole to ground)	kV_{DC}	640	640	640
Base power	MVA	854	1,678	2,562
AC current	AC	580	1,140	1,740

Data for ±640 kV symmetric base modules, typical values

Converter	DC voltage	DC current	DC cable	Sending power	Receiving power (MW)						
types	kV	A	Cu in mm²	MW	Back-to-back	50 km	100 km	200 km	400 km	800 km	1,600 km
M10	640	627	300	810.2	794.9	792.6	790.2	785.5	776.0	757.1	-
M11	640	1,233	1,200	1,593.2	1,563.2	1,561.0	1,558.7	1,554.1	1,544.9	1,526.5	1,489.8
M12	640	1,881	2,400	2,430.6	2,384.8	2,382.0	2,379.1	2,373.5	2,362.2	2,339.5	2,294.2

Transfer capability for different cable lengths, typical values for ±640 kV symmetric base modules.

4.2.6 Asymmetric base modules

As an alternative to symmetric (±) DC voltages from the converter, an option has been introduced to make an asymmetric DC voltage possible, i.e., voltage from ground to the chosen DC voltage level of the pole. Two asymmetric base modules can also be coupled together into a bipolar arrangement, either from the beginning or through expansion at a later stage. (see figure below)

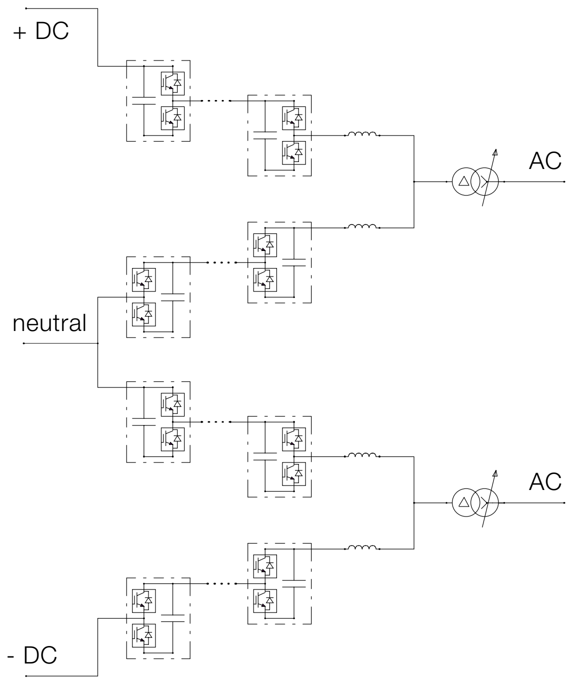
The asymmetric base modules are typically beneficial for transmission systems with:

- high requirements of reliability and/or availability by using a bipolar arrangement so that only 50 percent of the power is lost following a fault (N-1 criterion)
- Need for staged increase of transmitted power
- Applications with ground or sea electrodes in order to save the investment cost of one cable or OH-line section

HVDC Light® asymmetric modules		AC Currents 580AAC	AC Currents 1140AAC	AC Currents 1740AAC
DC Voltages	80 kV_{DC}	M1A	M2A	M3A
	150 kV_{DC}	M4A	M5A	M6A
	320 kV_{DC}	M7A	M8A	M9A
	500 kV_{DC}	M10A	M11A	M12A
	640 kV_{DC}	M13A	M14A	M15A

In an asymmetric base module configuration, the ratings and the transfer capability for different cable lengths follow the same principles as for the symmetric configurations described above. The only difference is that only half of the power is available.

Bipolar HVDC Light® scheme.

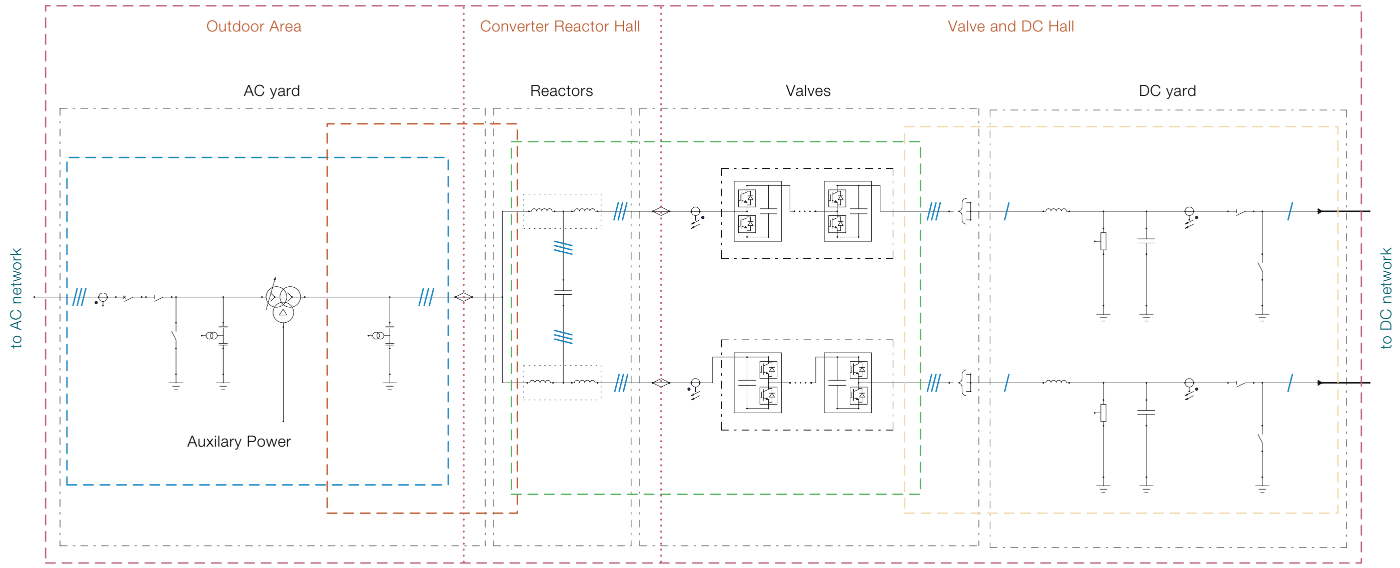


4.2.7 Selection of base modules for cable projects

The optimization of an entire project, including both converters and cables, must be performed separately for each specific business case, since active/reactive power demand, loss evaluation, cable length, cable cross-sectional area and cable installation must be considered. In general, it is more economical to choose a lower voltage and higher current for short distances. For longer distances, it is more economical in most cases to choose a higher voltage, even if a higher DC voltage increases the cost of the converters. A choice of either a symmetric or asymmetric converter type is typically based on the distance between terminals, reliability requirements, need for staged increase of power capacity and the possibility of using electrodes.

4.3 Main circut & station design

Single-line diagram of an HVDC Light® converter.



4.3.1 Power transformer

The transformer is a single-phase or three-phase AC power transformer with a tap changer, subjected to more harmonies compared to conventional AC transformers. However, for asymmetrical configurations, the transformer will be exposed to a DC-offset in the valve side AC voltages, which will result in a slightly more complicated transformer design. The tap changer is generally located on the valve side for a symmetrical configuration and on the network side for an asymmetrical configuration, since the tap changers have difficulty in handling the DC-offset.

Spare power ABB transformer at an HVDC site.

4.3.2 Converter reactors

The converter reactor is one of the key components in the converter station, the main purpose of which is to:

- provide active and reactive power control. The fundamental frequency voltage across the reactor defines the power flow (both active and reactive) between the AC and DC sides.
- limit short-circuit currents through the valves. The converter reactor impedance, in combination with the transformer impedance, defines the short circuit current for the valve diodes.

There are two converter reactors per phase, one for the positive and negative valve arm respectively, which each consist of vertical coils, standing on insulators. The CTL converter reactors are no longer stressed by large switching voltages, as was the case in the conventional two-level converter topology, but carries both ac and dc current.

4.3.3 Capacitors

The main capacitance for the CTL converter topology is distributed and integrated as a part of each valve cell, instead of being placed at each pole, as in the two-level topology. A pole capacitor also exists for the CTL converter, but is considerably smaller. The cell capacitor is charged or discharged, depending on the current direction, each time the cell is switched. The cell capacitor is a dry type capacitor.

4.3.4 AC filters

The output voltage from a CTL converter topology is already of sinusoidal character with low harmonic content, but the possible need for AC filters is mainly decided by the requirements put on filter performance, e.g. permissible voltage distortion, and the harmonic network impedances at the point of connection.

Typical requirements on filter performance are:
Individual harmonic distortion ≈ 1 percent
Total Harmonic Distortion (THD) ≈ 2 percent

The above indices are all based on the voltage measured at the AC point of connection and are direct measures of voltage quality.

4.3.5 DC filters

For CTL converters directly coupled to a DC cable, no additional DC filters are generally considered necessary, since the inherent suppression of any harmonics is sufficient. However, overhead lines directly coupled to the converter station will require a more detailed investigation and the final outcome mainly depends on the project-specific requirements put on filter performance.

A typical requirement can be expressed as an equivalent weighted residual current fed into the DC transmission at each station. The current is calculated as where:

- Ieq is the psophometrically weighted, 800 Hz equivalent disturbing current
- Ih is the vector sum of harmonic currents in cable pair conductors and screens at harmonic h
- Phf1 is the psophometric weight at the frequency of h times the fundamental frequency

4.3.6 High-frequency (HF) filters

The necessarily high dv/dt in the switching of the valves means that HF noise is generated. To prevent this HF noise from spreading from the converter to the connected power grids, particular attention is given to the design of the valves, to the shielding of the housings and to ensuring proper HF grounding connections.

To further limit HF interference, Radio Interference (RI) filters are normally installed. If power line carrier (PLC) systems are used nearby in the connected power grid, additional PLC filters may be required.

4.3.7 Valves

The IGBT position

The semiconductor used in HVDC Light® is the StakPak™ IGBT (insulated gate bipolar transistor) from ABB Semiconductors. As a conducting device, the bipolar transistor with its low forward voltage drop is used for handling high currents and instead of the regular current-controlled base. The IGBT has a voltage-controlled capacitive gate, as in the MOSFET device. To increase the power handling, six IGBT chips and six diode chips are connected in parallel in a sub-module. A StakPak™ IGBT has two, four or six sub-modules, which determine the current rating of the IGBT.

A complete IGBT position consists of an IGBT, a gate unit, a high-voltage board, an RC-snubber and a water-cooled heat sink. Each gate unit includes gate-driving circuits, surveillance circuits and optical interface. The gate-driving electronics control the gate voltage and current at turn-on and turn-off, in order to achieve optimal turn-on and turn-off processes of the IGBT. The voltage across the IGBT during switching is measured, and the information is sent to the valve control unit through an optical fiber. The high-voltage board connected across the IGBT provides the gate unit with the current needed to drive the gate and feed the optical communication circuits and the control electronics.

The IGBT cell

An HVDC Light® valve is built up by cells. A cell consists of two switches, each with a number of series connected StakPak IGBTs and one capacitor module. One cell can be seen as a conventional two-level converter, where all IGBTs in the same switch are switching simultaneously. One of the switches can, during on state, lead the current through the cell capacitor, whereas the other switch can bypass the capacitor. The flexibility of the IGBT as a semiconducting device also makes it possible to block the current immediately if a short circuit is detected.

The valve arm

In order for the converter to be able to handle high voltages, several cells are connected in series. A set of series-connected cells from the AC phase to the DC pole is called a valve arm. The main advantage of using this topology is that each switching only corresponds to a small voltage step, minimizing the harmonics generated by the converter. An HVDC Light® converter has six valve arms, two for each phase. The diagram below shows the principle schematics of an HVDC Light® converter.

Mechanical design

The converter valves are normally mounted in valve halls and built up by a number of series-connected, mechanically constructed IGBT cells.

The valve is suspended from the ceiling in the valve hall by polymeric insulators, which makes the valve resistant to earthquakes and other movements. To make a compact design, special corona shields are attached to the valve structure. The IGBTs are water cooled and the water pipes are placed in the bottom of the valve to minimize the risk and consequences of water leakage. All IGBTs and heat sinks in a module are mounted tightly together under very high pressure, in order to minimize contact resistance and increase cooling capacity. The module is pressed together with glass-fiber bolts, fulfilling both insulation and mechanical strength. The assembling method with IGBT cells hanging in the valve hall, together with controlled humidity levels, makes it possible to reduce the distances between high-voltage parts and the surroundings. This means that most of the HVDC Light® converter parts can be pre-assembled at the production location to minimize the assembly work on site.

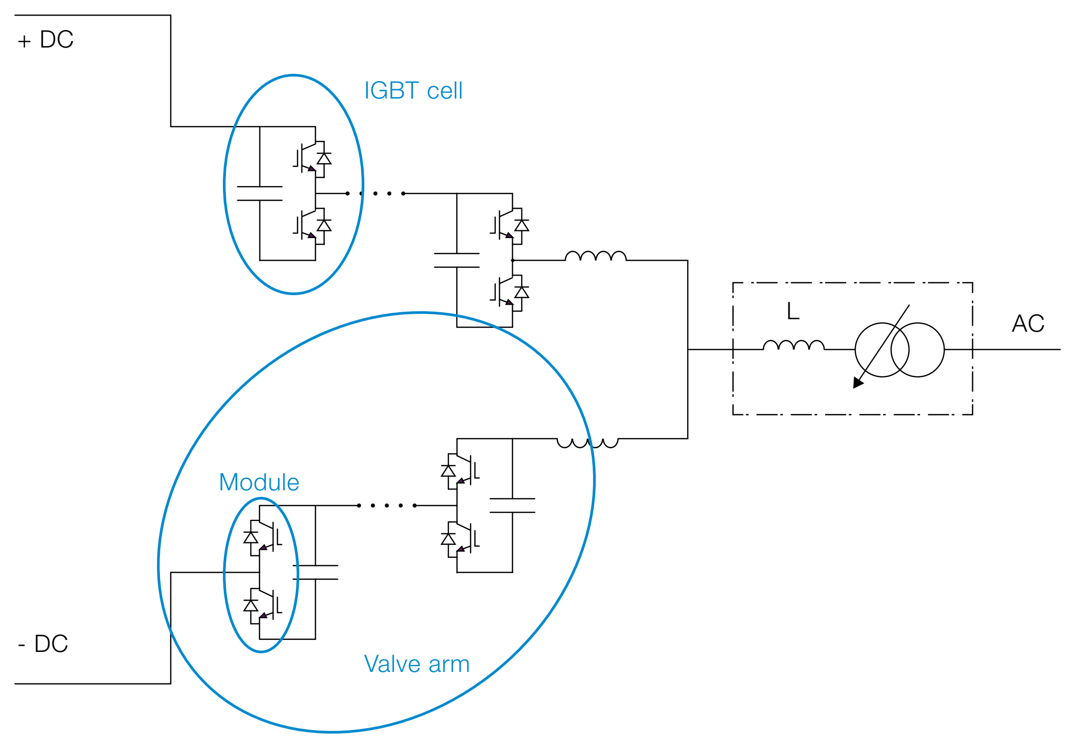
StakPak™ IGBT with six sub-modules.

Valve testing

The applicable standard for HVDC Light® converter valve testing is IEC 62501. This standard defines how to perform relevant testing for assuring adequate electromechanical design, voltage and current withstand capability, production quality etc. The tests are divided into dielectric, operational and production tests. The dielectric test verifies the electromechanical design with respect to voltage, whereas the operational test verifies the operation of the valve, i.e. current, voltage and temperature stresses. Production tests are performed on every IGBT module before delivery, thus ensuring quality and consistency in the production.

1 Principle schematic of an HVDC Light® converter (one phase) I 2 One double cell I 3 One IGBT module.

1



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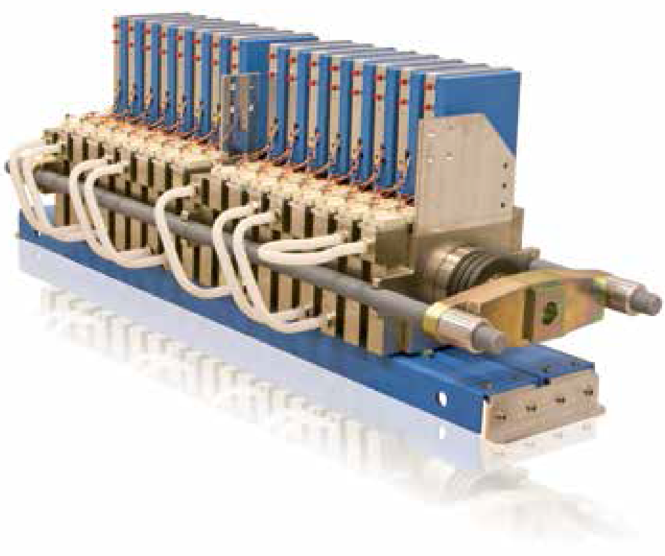


4.3.8 Valve cooling system

All HVDC Light® positions are equipped with water-cooled heat sinks providing high-efficiency cooling. To be able to use water as cooling liquid in direct contact with high voltage potentials, it is of great importance that the water has very low conductivity. The water is circulating through the heat sink in close contact with each IGBT, which efficiently transports the heat away from the semiconductor. The cooling water circuit is a closed system, and the water is cooled through heat exchangers using either air or a secondary water circuit as cooling medium. The water in the valve cooling system passes continuously through a de-ionizing system, to keep the conductivity of the water low. The temperature of the water in the valves is controlled by a MACH2-based cooling control system, for example regulating the number of fans to be operated in order to achieve the necessary cooling capacity. In addition to temperature measurements, the cooling system is also equipped with sensors for pressure, water flow, level and conductivity, and it controls motor-operated valves, pumps and fans. If necessary, electrical heaters or glycol can be added to prevent the water from freezing if the converter station is located in a cold area.

All major parts of the valve cooling system are provided with redundant equipment. The control system consists of two separate systems that measure all parameters using different transmitters, all in order to minimize the risk of an unwanted stop. Both systems are able to control the two main pump motors, and the low-voltage switchgear has switchover functions to ensure uninterruptible operation. The software also performs weekly changeovers of the pumps in operation, in order to ensure equal wear of the equipment. The redundancy of all the equipment also simplifies the maintenance of the valve cooling system. If maintenance is necessary, it is possible to change which pump will run manually directly from the operator computer. Some parts of the cooling system can be closed and disconnected to allow maintenance to be carried out without interrupting the power transmission. The valve cooling system used for HVDC Light® is based on the valve cooling system used for thyristor valves in conventional HVDC converters since 1980.

Valve cooling system.

4.3.9 Station service power

The station service power system is vital for reliable operation. The design of the station service power focuses on:

- Redundant power supplies, one from the internal AC bus and one from an external source.
- The supply to the internal AC bus can be taken from an additional winding on the converter transformer, if available. In this way, the power supply is guaranteed at all times when the station is in operation. The output voltage is normally around 20 kV, which means that an intermediate transformer is necessary to provide a 400 V system. The external power supply is generally taken from a local AC system and is used as back-up source.
- Duplication of all critical parts, valve cooling pumps, station batteries and battery chargers.
- Automatic changeover: the incoming feeders to the 400 V switchgear have automatic changeover control. The supply coming from the internal AC bus is preselected as the primary supply, and the supply from the external local AC system is preselected as the backup supply. If the preselected supply fails, changeover to the backup supply takes place within a preset time. When the preselected supply returns, the system changes back to the primary supply.
- Duplication of all critical equipment.
- Valve cooling pumps: the duplicated valve cooling pumps are controlled by frequency converters for maximum flexibility. The frequency converter also makes it possible to use a DC backup source to keep the pump running, if auxiliary power is lost.
- Station battery system: the control equipment and other DC loads are supplied from a duplicated battery system with a backup time of at least two hours. Critical AC loads within the control equipment, such as servers, computers, LAN switches, etc., are supplied from a DC/AC inverter fed from the station battery and with an automatic switchover to the alternative AC supply in the event of inverter failure or overload.

4.3.10 Fire protection
The design of the fire protection system is in accordance with NFPA (National Fire Protection Association) and with the requirements of all applicable authorities.

In general, all areas with sensitive equipment are equipped with air sampling systems. The air sampling system can detect smoke at a very early stage, which can prevent unnecessary tripping or shutdown of the station.

If required, the areas with air sampling systems can also be protected with gas or water mist extinguishing systems in accordance with NFPA 2001 or NFPA 750. If a water pumping system is required, it will consist of one electric pump and one standby diesel-driven pump. A ring main water loop will then be located on the site (underground). It is connected to an isolation valve that will bring redundancy in the ring main loop for firefighting water. Fire hydrants will be positioned at strategic locations around the site area close to the main loop. Water supply storage will be connected to the firefighting water loop. The signals from the detection system and the pumps will be connected to a fire alarm panel in the operator control room.

4.3.11 Civil, installation and commissioning
General
- Both the civil engineering works and equipment installation are normally contracted to a local contractor, who will perform the works under the supervision of ABB engineers.

On-site inspection and test activities comprise:
- Verifications and inspection during civil engineering work
- Pre-installation verifications
- Verifications during installation
- Equipment tests

Testing of subsystems of the HVDC system
- Subsystem functional (circuit) tests
- Start up of auxiliary systems

System tests of the HVDC system
- Terminal test
- High-voltage energizing
- Terminal operation
- Transmission test

In addition to the tests specified above, acceptance tests will be performed according to the contract agreement. During inspections, the environmental impact requirements specified in the various design drawings will also be verified. All tests will be performed or supervised by ABB commissioning engineers and ABB experts. All tests under high-voltage conditions, terminal tests and transmission tests will be directed by ABB's test manager with the assistance of ABB commissioning engineers, but under full operational responsibility of the customer's operational organization.

4.3.12 Availability
When designing a modern HVDC Light® transmission system, one of the main design objectives is to minimize the number of forced outages and to maximize energy availability (EA).

HVDC Light® transmission is designed according to the following principles in order to assure high reliability and availability:
- Simple station design
- Use of components with proven high reliability
- Automatic supervision
- Use of redundant control systems and equipment
- Available spare units
- The design must allow maintenance activities (forced and scheduled) to be performed with minimum curtailment of the system operation
- Scheduled maintenance that requires link shut-down must be minimized

4.3.13 Maintainability
Unavailability due to scheduled maintenance depends both on the design of transmission and on organization of the maintenance work. The modern design of HVDC Light®, which incorporates extensive redundancies for essential systems such as cooling systems, duplicated control systems and station service power, allows most maintenance work to be done with no interruption of operation. Scheduled unavailability per year is generally estimated to be below 0.5 percent.

4.3.14 Quality assurance
ABB has developed an effective and efficient quality assurance program complying with ISO 9001 (certified by Bureau Veritas) and an environment management system complying with ISO 14000. The know-how acquired by long experience of HVDC projects, solid technical resources and closely developed relations with key sub suppliers ensures reliable products in compliance with the specification. All equipment is in line with applicable IEC standards.

The quality assurance program provides tools that ensure the work in different phases is executed in a predictable manner. Several systems for feedback of experience are used, including follow-up and testing during equipment manufacturing, installation, commissioning and commercial operation.

ABB is actively working with health, safety and environmental plans to ensure that laws, regulations, internal instructions and routines are followed. ABB started out with an environmental program in 1995 and was certified in accordance with ISO 14001 in 1998 and according to OHSAS 18001 in 2009.

4.3.15 Acoustic noise

A major part of the equipment that generates noise is located inside the building, and this noise can be successfully mitigated by appropriately designed acoustic properties of the walls and roof.

The sound requirements usually apply to the areas outside the station; the space inside the station and the inside of the buildings varies depending on national regulations.

Common sound requirements for areas outside the station can typically be:
– At the property line ~ 60-65 decibels (dB)
– At the nearest residences ~ 40-45 dB

Typical noise sources in the HVDC Light® station are:
– Power transformers
– Converter reactors
– Cooling fans for cooling systems
– Ventilation openings and facades of the equipment buildings
– Air-conditioning equipment

Prediction model

The calculation to predict the sound contribution from equipment is usually done in a three-dimensional (3-D) model of the plant and its surroundings. All significant sound sources in the plant are included in the model. The most essential elements of station surroundings which may influence the sound propagation from the station are also included. The 3-D model makes it possible to study different possible layouts and different configurations of the equipment for the future station. The result of the prediction may be shown as a sound contribution map for the area around the station and can also be supplemented with tables containing the exact sound level values for the chosen locations of interest.

4.4 System engineering

4.4.1 Feasibility study

During the development of a new project, it is common to perform a feasibility study in order to identify any special requirements to be met by the system design. ABB can supply models of HVDC Light® transmissions in PSS®E, DIgSILENT PowerFactory, PSS®NETOMAC as well as PSLF simulation tools.

4.4.2 System design

The flow diagram below illustrates the types of engineering required in a delivery project.

The main circuit design includes the following design studies:
– Main circuit parameters
– Single-line diagram
– Insulation coordination
– Harmonic performance
– Radio interference study
– Transient overvoltages
– Transient currents
– Calculation of losses
– Availability calculation
– Audible noise study

Control system design specifies the requirements to be met by the control and protection system, and all the main circuit apparatus. Control system characteristics are optimized during the detailed design phase. The rating includes all relevant continuous and transient stresses. The auxiliary system design includes the design of auxiliary power, valve cooling, the air-conditioning system and fire protection system. The layout of the main circuit equipment is determined by the electromechanical design, and the station design specifies buildings and foundations.

4.4.3 Validation

DPS

The performance of the combined AC and DC system is validated in a dynamic performance study (DPS). The setup includes a detailed representation of the main circuit equipment, and the control model is a copy of the code that will be delivered to site. The AC systems are represented with a detailed representation of the immediate vicinity of the AC system. Typical faults and contingencies are simulated to show that the total system responds appropriately.

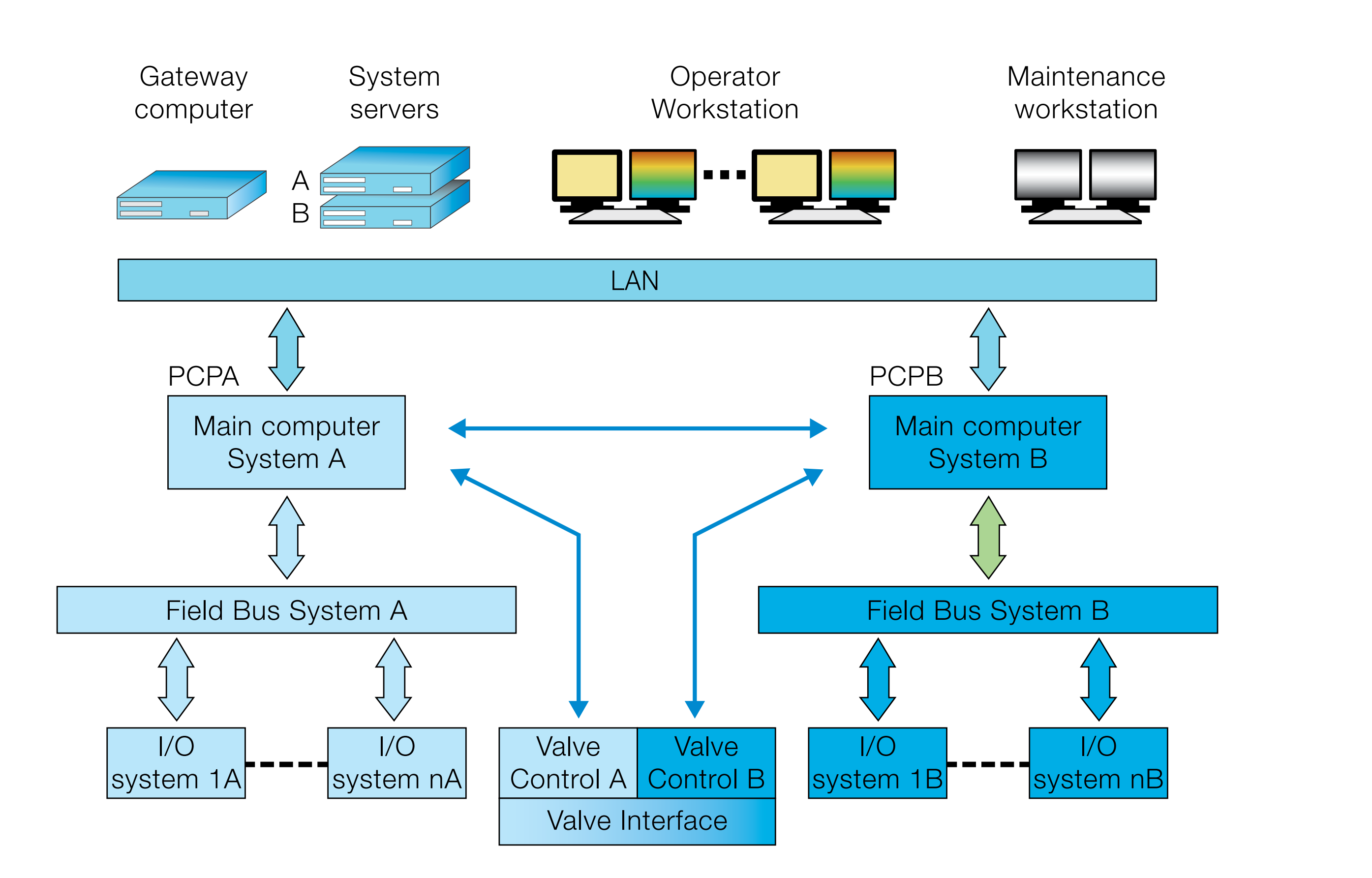
FST

During the factory system test (FST), the control equipment to be delivered is connected to a real-time simulator. Tests are performed according to a test sequence list in order to validate that the control and protection system performs as required.

Site test

During the commissioning of the converter stations, tests are performed according to a test sequence list in order to validate the specified functionality of the system.

MACH2 Control and Protection system structure.



4.5 HVDC Light® control and protection system

To operate an HVDC Light® transmission as efficiently as possible, a powerful, flexible and reliable control and protection system is required. To fulfill current and future requirements, ABB has developed a fully computerized control and protection system using state-of-the-art computers, microcontrollers and digital signal processors connected by high-performance industrial standard buses and fiber optic communication links.

The system is called MACH (Modular Advanced Control for HVDC and SVC), and is designed specifically for converters in power applications. All critical parts of the system are designed with inherent parallel redundancy and use the same switchover principles as used by ABB for HVDC applications since the early 1980s.

Because of the extensive use of computers and microcontrollers, it has been possible to include very powerful internal supervision, which will eliminate periodic maintenance for the control equipment. As a consequence of placing all functions in computers and micro-controllers, software plays the most important role in system design. By using a fully graphical functional block programming language and a graphic debugging tool running on networked standard computers, it is possible to establish a very efficient development and test environment to produce high quality programs and documentation.

To achieve high reliability, quality is built into every detail from the beginning of the engineering design phase. This is assured by careful component selection, strict design rules and, finally, by the extensive factory system testing of the control system connected to a real-time HVDC simulator.

Developments in the field of electronics are extremely rapid at present, and the best way to ensure that the designs can follow and benefit from this is to build systems based on open interfaces. This is achieved by using international and industry standards, as these standards have long lifetimes and ensure that spare and upgrade parts are readily available.

4.5.1 Control and protection system design

The HVDC Light® control and protection system consists of the station control and monitoring servers, operator workstations, control and protection main computers, I/O systems and valve control units typically arranged as shown in the figure below. Thanks to the modularity and high performance of the MACH equipment, the type of hardware and system software used for an ABB HVDC Light® control system are the same as in a classic control system. In fact, only the application software and the valve control differs.

Control system redundancy design

The design criterion for the control system is 100 percent availability for the transmission system, i.e. no single point of failure should interrupt operation. Therefore, redundancy is provided for all system parts involved in the power transfer. The redundant control systems are designed as duplicated and parallel systems acting as active or hot standby. At any time, only one of the two systems is active, controlling the converter and associated equipment. The other system, the standby system, is running but the outputs from that system are disabled.

Control system changeover

The system switchover commands can be initiated manually or automatically. If a fault is detected in the active system, the standby system automatically takes over control, becoming the active system. The internal supervision giving switchover orders includes hardware supervision, auxiliary power supervision, program execution supervision (stall alarm), memory testing and supervision of the communication. The faulty system (the previously active system) should be checked before being taken back into operation as the standby system. The switchover commands are always initiated from the active system. This switchover philosophy means that a fault or testing activity in the standby system cannot result in an unintentional switchover. Furthermore, a manual switchover order to a faulty standby system is not possible.

Protection redundancy design

Both systems have main computer protection, with identical protection functions fed from separate primary sensors. Normally, the protection computers in both systems are active simultaneously. It is enough that the protections in one computer detect a fault for a protective action to be initiated. In that way, the correct protective action can be taken even if some measurement is malfunctioning.

To improve the overall reliability of the HVDC Light® transmission, it is important to avoid unnecessary trips caused by control problems. Therefore, some protections initiate a fast changeover of control system before a trip order is given. If the redundant control system is healthy and successfully re-establishes undisturbed power transfer on the HVDC link, the protections in both systems will reset and not time out to trip.

Self supervision

Inadvertent trips are avoided as each system is provided with extensive self-supervision, which further enhances system reliability. Examples of methods for self-supervision are:
- Inherent supervision in measuring systems
- Supervision of data bus communications
- Supervision of auxiliary power

Any detected failures in the control and protection hardware will result in a request for changeover, which will be executed if a standby system is available and ready to take over. Otherwise, depending on the severity of the fault, the system either stays active and only produces an alarm, or orders a trip. As a last resort, there is also hard-wired backup trip logic to handle the loss of both systems.

4.5.2 Main computers

To take full advantage of the rapid electronic developments, the main computers of the MACH system are based on high-performance industrial computer components. This ensures that ABB can take full advantage of the extremely rapid developments in the field of microprocessors and design the control and protection system for the highest possible performance. The main computers are built around COM Express modules with Intel® Core™ processors, giving the main computers very good performance and, at the same time, very low power consumption. The low power consumption means that the main computers can be designed with self-convection cooling. Problems with dust and maintenance requirements connected with forced air-cooling are therefore avoided. The main computers are designed for mounting in the rear-mounting plane of control and protection cubicles.

4.5.3 I/O system

The interface between the main computers and the rest of the HVDC facility is the I/O system. It is placed in cubicles where electric signals to and from the main circuit equipment is connected to I/O boards. These boards can be of different types such as digital input, digital output, voltage and current measurements and switch control boards. The boards are placed in a rack, where the backplane enables communication between the boards. This modular design ensures that it is easy to adapt the I/O system to project-specific requirements and also facilitates easy addition of new functions to the control system. Each redundant system has its own full set of I/O boards. The I/O cubicles are connected to the main computer cubicles using optical field bus connections, to avoid electromagnetic interference.

4.5.4 Valve control unit

The VCU is composed by two sets of valve control boards working in pair to achieve full redundancy. Each valve control board is connected to a number of cell boards, where each cell board interfaces optically to the 16 gate units in a cell, one for each IGBT, via an electro-optical interface. The VCU receives control signals from their respective redundant control system and forwards them to the cell boards. Only the active system has full access to the gate unit and will send firing pulses in one fiber, while both the active and standby system has access to the information sent back by the gate unit in a second fiber. Both the capacitor and cell voltages are supervised by the cell boards, as well as the IGBTs. There is also an internal supervision in the VCU, monitoring the condition of the IGBTs and capacitors, as well as its own hardware and software.

4.5.5 Communication

The communication inside the converter station uses a hierarchy of serial buses. A general rule for the use of serial buses is to use standardized buses and protocols. The objective is to ensure a long economic lifetime for the buses and to ensure that the components used to build the bus structures are available from independent sources.

Local communication

The local area network used in the pole is based on the ubiquitous IEEE 802.3 standard (Ethernet). The SCM LAN is used to transfer data between the control and protection main computers and the various clients on the network such as servers and operator workstations.

Field buses

• CAN bus

ISO standard buses, ISO 11898, also known as CAN (Control Area Network), are used for communication with binary type I/O devices (disconnectors and breakers etc.), within the I/O systems. The CAN bus combines a set of properties important for use in an HVDC station, namely:

- It is a high-speed bus with an efficient short message structure and very low latency
- There is no master/slave arrangement, which means that the bus is never dependent on the function of any single node to operate correctly
- Efficient CRC checks and hardware features to remove a faulty node from the network
- The CAN communication within an I/O system is performed via the backplane of the I/O racks. Extension cables with shielded, twisted pairs are used for the connection of adjacent racks in the cubicle.

• eTDM bus

Fiber optic communications on eTDM are used for communication outside of the cubicles or control room. The eTDM bus in the MACH2 system is a high-speed, single fiber, optical data bus for digitized analog measurements. The eTDM bus is characterized by large data carrying capacity, very low latency and “no jitter” operation. This is absolutely essential when used to feed the HVDC controls with high bandwidth measured signals. Each eTDM bus is able to transmit over 300,000 samples per second (one sample every 3 μS). Thanks to the high-speed-performance of the bus, it is also possible to include the binary data from the CAN bus of the I/O systems as an “overlay” on the eTDM bus communication.

• EtherCAT

EtherCAT is a high performance Ethernet based Field bus used for communication between I/O units and the main computers. The bus is used for analog and digital signals using a sampling speed of up to 10kHz.

Remote communication

If station-to-station communication is included, it is handled by communication boards in the main computer of the pole control and protection (PCP) cubicles. This pole-level communication gives a more robust design than a centralized station-level telecommunication unit. The communication is synchronous and conforms to ISO 3309 (HDLC frames) for high security. If available, a LAN/WAN type of communication is also used. This eliminates the need for special communication boards and provides even higher performance. ABB has experience with all types of telecommunication, ranging from 50 and 300 bps radio links, via the 1,200, 2,400 or 9,600 bps communication links using analogue voice channels, up to high speed links obtained with optical fiber connections.

4.5.6 Control functions

Each HVDC Light® converter is able to control active and reactive power independently by simultaneously regulating the amplitude and phase angle of the fundamental component of the converter output voltage (refer to section 4.1.3). The general control scheme of one converter station is shown in the figure below.

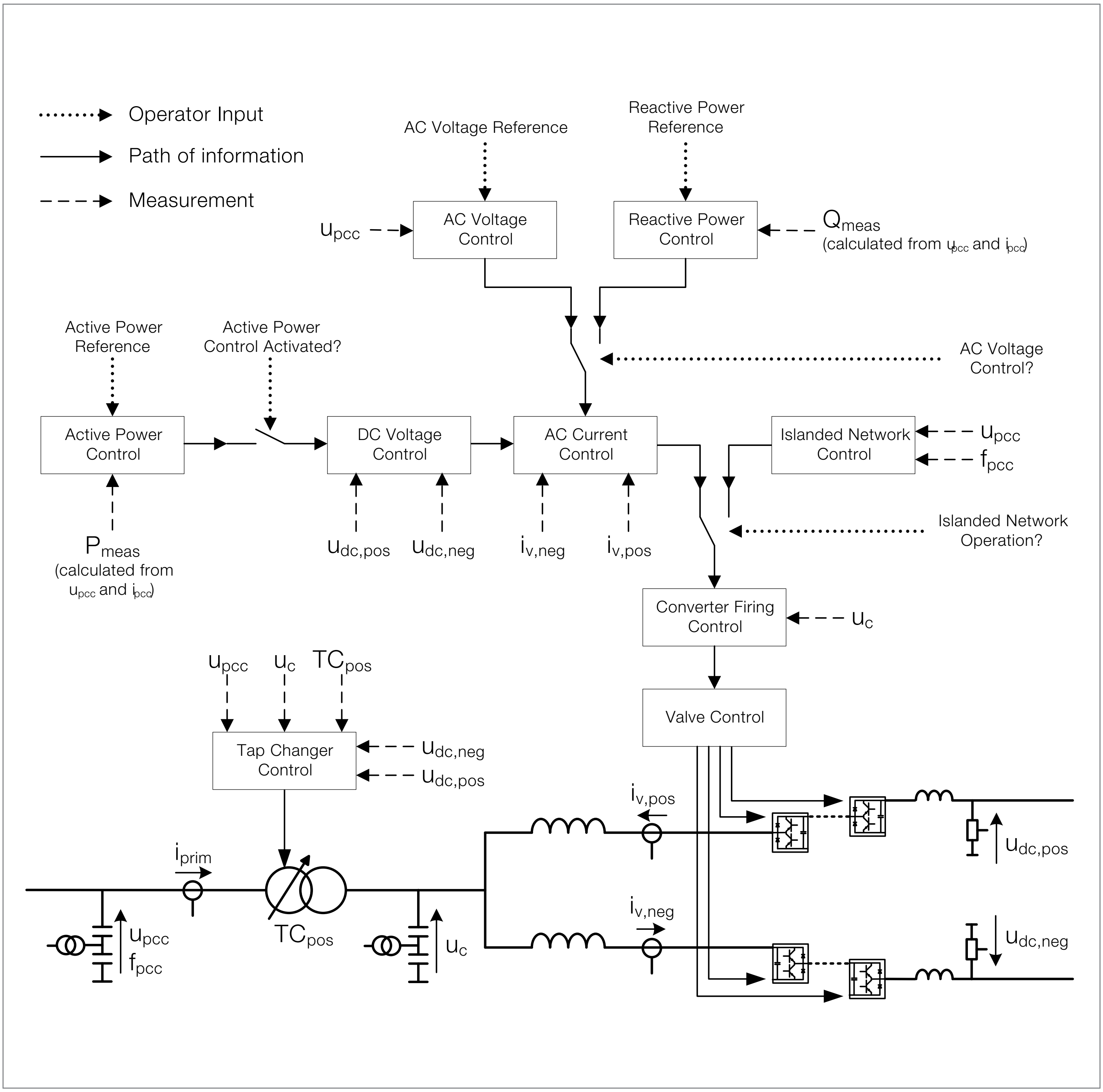
DC voltage control

Forces the maximum DC system voltage to track the reference setting via feedback control, and produces an active current order. This control function is not accessible to the operator.

Active power control

The active power control generates a contribution to the DC voltage reference depending on the active power reference. This voltage difference between the stations drives the desired DC current. A feedback control keeps the power at the desired value. When the operator orders a new power setting, the power is ramped to the desired level at a selected ramp speed. It is possible to ramp through zero transmitted power when reversing power direction. Only one station is allowed to be in active power control mode, and only when the other station is controlling the DC voltage. If a switch between active power control and DC voltage control is initiated, this is supervised and coordinated by the control software to make a smooth transition. All other power orders in the system, such as emergency power control actions and frequency control contribution, are also routed via the active power controller. This is to ensure smooth transitions between normal operation and automatic system actions.

Control block diagram with simple single-line diagram.



Reactive power control

The HVDC Light® converter can either generate or consume reactive power, independently in each station. The reactive power control tracks the reference value and generates a current reference, controlling the reactive power at the network side of the transformer to a level set by the operator. A new operator order is fulfilled by the control system at a selected ramp speed, giving a smooth change in reactive power. If the AC voltage is outside the predefined limitations, the converter control will no longer follow the reactive power order; instead it will temporary switch to AC voltage control in order to keep the AC voltage within limits.

The selection of AC voltage control and reactive power control is exclusive; only one of these control modes is active at a time. The system will update the reference value automatically at start-up, shut-down or when changing between the control modes during operation, to have minimal effect on the AC network.

AC voltage control

If the converter station is set to AC voltage control, the control system tracks the internal AC voltage reference and generates a reference for the current control. AC voltage setting and ramp speed is adjustable by the operator. In AC voltage control, the reactive power can be any value within the PQ capability, as described in 4.1.3. The internal AC voltage reference may differ slightly from the operator setting depending on the droop gain. This means that a higher reactive power load will give a larger difference from the AC voltage order, ensuring stable operation also if the UQ characteristic of the network is flat. This is especially important in strong AC networks.

AC current control

The AC current control includes two types of regulators; one controlling the active current component and one controlling the reactive current component. The outputs from the DC voltage control and AC voltage or reactive power control serve as inputs to the AC current control. The AC current control consists of the feed-forward of AC bus voltage, the feed-forward of current order, depending on voltage drops in the reactor, and the feedback control of the AC current. This control function is not accessible to the operator.

Converter firing control

A phase-locked loop (PLL) is used to synchronize the converter control with the line voltage. The input to the PLL is the measured converter bus voltage and the output is a time dependent phase angle. The switching pulse generator uses the phase angle and pulse width modulation (PWM) to generate the switching order, according to the AC current reference from the AC current control. The resulting switching pulses are then transmitted to the valve control. This control function is not accessible to the operator.

Tap changer control

This device controls the stepping of the transformer tap changer. The purpose is to keep the converter bus voltage and the relationship between the AC and DC voltage (modulation index) within specified ranges.

Islanded network control

If the converter station is connected to an islanded network, the reactive power and active power is determined by the difference between the total load and total generation within the islanded network. This means that the converter operates as an infinite source, instead of the normal mode of controlling the active and reactive power to a set point. When a load is connected, there will be an instantaneous change in the transmitted power corresponding to the size of the load.

4.5.7 Additional control functions

Emergency power control

The fast control of active and reactive power can enhance grid dynamic performance following disturbances. For example, if a severe contingency threatens the systems transient stability, fast active power run-back, run-up or an instant power reversal can be used to maintain synchronized grid operation. Emergency power actions may be initiated by external inputs or signals derived within the control system.

Frequency control

HVDC systems can enhance stability problems by drawing energy from the remote system, and thereby control the local network frequency. Because of its ability to change the operating point instantaneously, HVDC can feed (or reduce) active power into a disturbed system and obtain a much faster frequency control than a generator. Coordination with other control functions, such as emergency power control and islanded network control, is performed automatically in the control system.

Damping control

A converters' fast control capability can be used to mitigate low-frequency oscillations in the grid by active and/or reactive power modulation. In particular inter-area oscillations, where traditional power system stabilizers are less effective, can generally be handled effectively by means of a well-designed HVDC modulation scheme. The ability to simultaneously modulate active and reactive power also makes the damping effect of HVDC less dependent on its converter location in the AC network.

Overvoltage functionality

The control system may be configured to react to AC voltage rises above predefined limits. It will then order the converter to consume as much reactive power as possible in order to get the AC voltage back within the normal operating range.

4.5.8 Protections

Protection system philosophy

The purpose of the protection system is to ensure the prompt removal of any element of the electrical system in the event of a fault. The protective system is aided in this task by the AC circuit-breakers, which disconnect the AC network from the converters and are capable of de-energizing the converter transformer.

Protective actions and effects

When a protection operates, the following fault clearing actions are chosen from, depending on the type of fault:

Alarms

Alarms are sometimes generated as a first action to notify the operator that something is wrong, but the system will still continue in operation as before the alarm.

Temporary blocking

If the converter cells suffer from high current or voltage, a temporary turn-off pulse is sent to all IGBT positions. When the current and voltages returns to a safe level again, normal operation is resumed.

Permanent blocking

The permanent blocking sends a turn-off pulse to all IGBT positions and always precedes the AC circuit-breaker trip.

AC circuit-breaker trip

Tripping of the AC circuit-breaker disconnects the AC network from the converter equipment. All protective trip orders to the AC circuit-breakers energize both the A and B coils of the breakers through two redundant devices. Two redundant auxiliary power supplies also feed the redundant trip orders.

Set lockout of the AC circuit-breaker

If a trip order has been sent to the AC circuit-breaker, an order to lock out the breaker may also be executed. This is done to prevent the breaker from closing before the operator has investigated the cause of the trip. The operator can manually reset the lockout of the breaker.

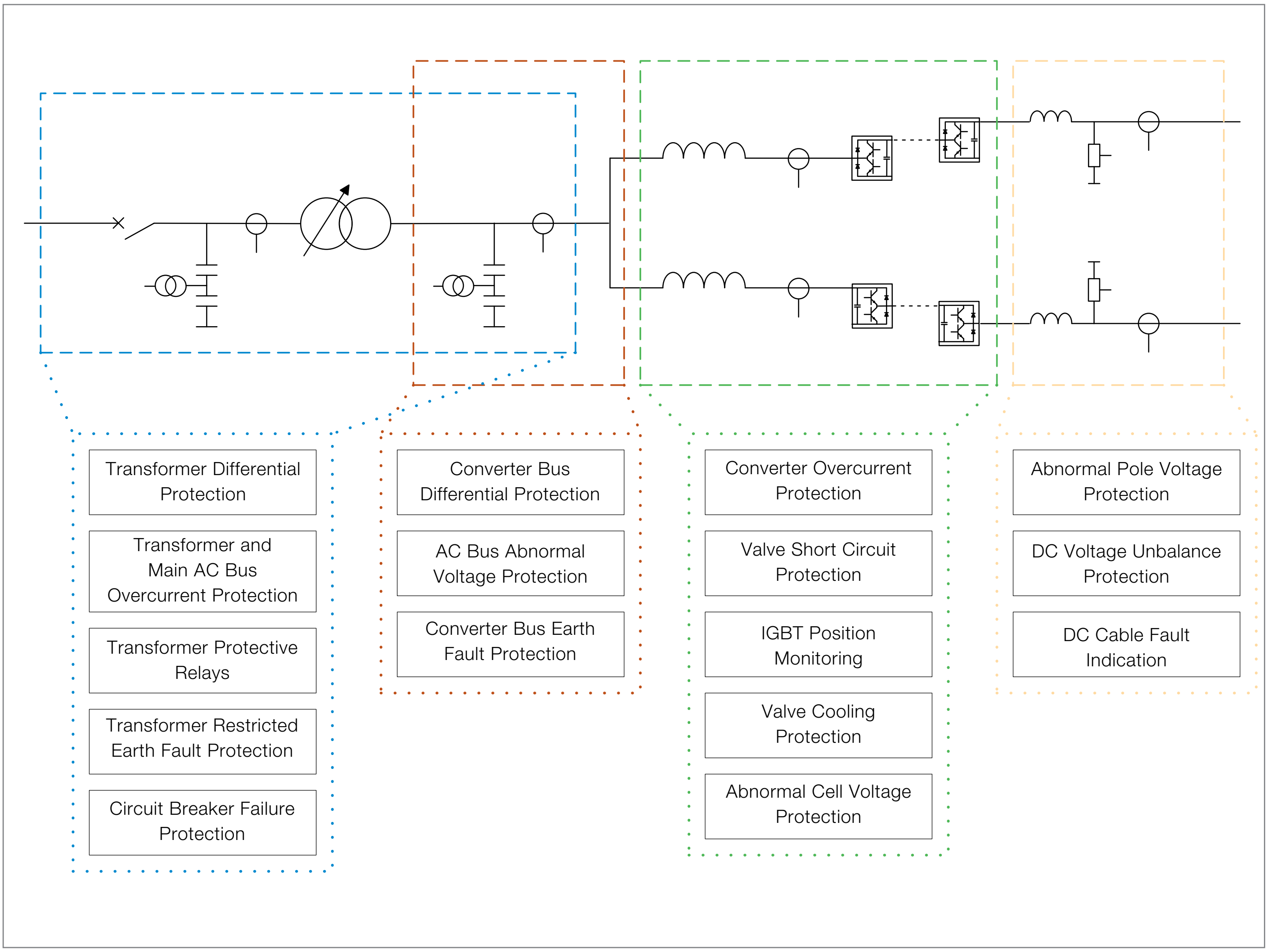
Pole isolation

The pole isolation sequence disconnects the DC side (positive and negative poles) from the DC cable. This is done either manually during normal shutdown or automatically by order from protections, for example a cooling water leakage.

Start breaker failure protection

At the same time as a trip order is sent to the AC breaker, an order may also be sent to start the breaker failure protection. If the breaker does not open properly within a certain time, the breaker failure protection orders retripping and/or tripping of the next breaker.

Simple single-line diagram with examples of protection functions.



4.5.9 Human-machine interface

A well-designed and flexible human-machine interface (HMI) is essential, and to avoid human errors, all parts of these systems must be easy to use. The HMI must be able to announce alarms and perform operator controls in a safe and reliable way. For example, several thousands of measured values, indications and alarms of different types need to be handled. All changes in the state of these signals must be recorded and time tagged with high resolution for accurate real-time and post-fault analysis.

The integrated HMI used by ABB, the Station Control and Monitoring (SCM) system, employs advanced software concepts with regard to system openness, flexibility and ergonomic aspects. The SCM system comprises several operator workstations (OWS) and servers.

The SCM system integrates a large number of features such as:

- Control of the HVDC Light® from process images
- Sequential event recorder
- Archiving of events
- Powerful alarm handling via list windows
- Effective user-defined data filtering
- Flexible handling of both on-line and historical trends
- On-line help functions and direct access to plant documentation
- Transient fault recording and analysis
- Remote control via gateway station communication interface

4.5.10 Maintenance of MACH

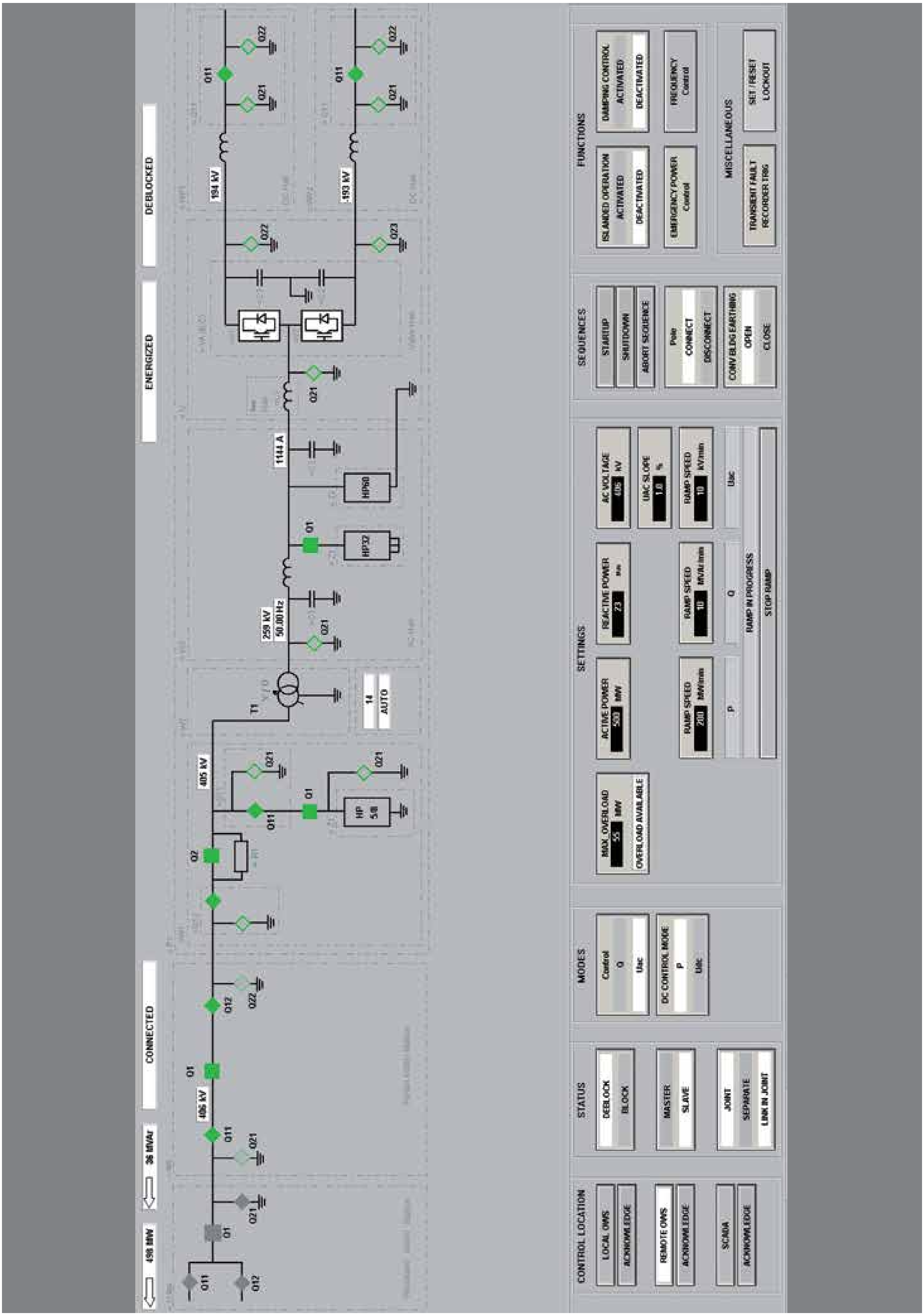
General

ABB MACH control and protection equipment is designed to be maintenance free, with the shortest possible repair times. Periodic maintenance is eliminated by the extensive use of self-supervision built into all microprocessor-based electronic units, and by the system's ability to check all measured values without disturbing the power transmission. The internal supervision of microprocessor-based systems includes hardware supervision, auxiliary power supervision, program execution supervision (stall alarm), memory test (both program and data memory) and supervision of communication. The operation of the field buses is monitored by a supervisory function, which continuously communicates with each individual node of the system. Any detected fault results in an alarm and switchover to the standby system. Due to the redundant design of the control system, corrective maintenance does not require shutdown of any main circuit equipment. Thanks to the versatile internal communication interfaces, it is easy to update software both in main computers and MACH2 boards remotely from a single engineering workstation. Software maintenance can also be performed from outside the station using remote access.

Transient fault recorder

The transient fault recorder (TFR) is integrated as a part of the control and protection software. The TFR is an invaluable analysis tool and outperforms old-fashioned external TFR's, as it always gives a correct representation of the important internal control signals. The TFR continuously samples the selected channels to be monitored for fault analysis. There is a predefined selection of protection and control signals, but also a number of channels which are available to be chosen freely by the operator. This makes it possible to monitor any internal signal in the control and protection software. As the TFR is an integrated part of the HVDC control system, it also runs in both the active and the standby systems. TFR data is stored in the COMTRADE format (IEEE C37.111-1991), and any standard program capable of interpreting the format can be used for post-fault analysis of the stored TFR records.

Typical control page with single line diagram for a HVDC Light® station.



5 HVDC Light® transmission technology

HVDC Light® technology is compatible with land and sea cables as well as overhead lines as means for transmitting the power in the transmission system.

5.1 HVDC Light® cables

HVDC Light® cables for land and sea transmission have been developed in conjunction with the converters to offer a matching cable technology. The development steps for cables are a result driven by demand for higher voltages and transmission capacity.

HVDC cables are generally much more efficient for long-distance transmissions than AC cables, particularly at higher powers. The reason is that AC cables must be rated for the capacitive charging current, in addition to the transmitted active current. The capacitive charging current is proportional to the length and the voltage of the AC cable and beyond a certain distance, there is no capacity left for the active power transmission. DC cables have no capacitive charging current, i.e. all the transmission capacity of the cable is available for active power transmission. The capacitive reactive power generated by long AC cables must be taken care of.

HVDC Light® polymer cables for HVDC are similar to XLPE AC cables, but with a modified polymeric insulation. XLPE cables have been used for AC since the late 1960s. The cables are designed to meet current and voltage ratings for the specified power transmission capacity and for the specified installation conditions. The inherent lifetime of insulating materials is better for DC than for AC, and gives the HVDC Light® system a longer lifetime. Mass impregnated cables can also be considered for HVDC Light applications.

Experience of 150 kV HVDC Light® cable projects

MurrayLink Land Cable, Victoria – South Australia	
137 km	HVDC Light® Cables with 1,400 mm² aluminum conductor
223 km	HVDC Light® Cables with 1,200 mm² aluminum conductor
400 pcs	Stiff cable joints
4 pcs	Cable terminations
Delivery year	2002
Operating experience very satisfactory; one fault attributed to external damage	

Experience of 200 kV HVDC Light® cable projects

EWIP land and sea cable, UK-Ireland	
150 km	HVDC Light® cables with 2,210 mm² aluminum conductor
373km	HVDC Light® cables with 1,650 mm² copper conductor
10.5km	HVAC 400kV XLPE Cables with 1,600 mm² aluminum conductor
10 pcs	Stiff cable joints
4 pcs	Cable terminations
12 pcs	HVAC 400 kV terminations
15 pcs	HVAC 400 kV joints
Delivery year	2012

5.1.1 General design of cables

Typical HVDC Light® cable designs have been previously shown. Cable parts include:

Conductor

The shape of the conductor is round and built up of compacted stranded round wires or, for large cross-sections, concentric layers of keystone-shaped wires. On request, the conductor can be water sealed, in order to block water penetration longitudinally in case of damage to the cable.

Insulation system

The HVDC polymeric insulation system consists of:
- conductor screen
- insulation
- insulation screen

The material, specifically developed for HVDC cables, is of the highest quality, and the insulation system is triple-extruded and dry-cured. The sensitive interface surfaces between insulation and conductive screens are not exposed at any stage of the manufacture of the insulation system. High-quality material handling systems, triple extrusion, dry-curing and super-clean insulation materials guarantee high-quality products.

Metallic screen

Copper wire screen, for land cables, with cross-section design for fault currents.

Metallic sheath

A lead alloy sheath is provided for submarine cables. A metal-polyethylene laminate may be provided for land cables. The laminate is bonded to the polyethylene, which gives excellent mechanical properties.

Inner jacket (for submarine cables)

A polyethylene sheath is extruded over the lead sheath. The polyethylene sheath provides mechanical and corrosion protection for the lead sheath.

Tensile armor (for submarine cables)

The tensile armor consists of galvanized round steel wires close to each other twisted round the cable. The tensile armor is flooded with bitumen in order to obtain effective corrosion protection. The tensile armor is needed when the cable is laid in the sea. The tensile armor also offers mechanical protection against impacts and abrasion for a cable that is not buried to safe depth in the seabed.

Outer sheath or serving

The outer serving for submarine cables consists of two layers of polypropylene yarn, the inner one impregnated with bitumen. The polypropylene yarn is a semi-wet covering. The outer sheath on land cables is normally a thermoplastic polyethylene (PE) sheath or an extruded PVC sheath. PE is a harder material, offering better mechanical protection, and is the first choice for most applications. PVC sheaths are classified as halogen material and are flame-retardant. The surface of the outer sheath may be provided with a thin conductive layer, which is simultaneously extruded with, and thus strongly bonded to, the non-conductive underlying jacket. This is useful to ensure the physical integrity of the cable in the post-installation test.

Standards and Recommendations

- Cigré, ELECTRA No. 171 Recommendations for mechanical tests on sub-marine cables
- Cigré Technical Brochure Ref No 219 "Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to 250 kV"
- IEC 60228 Conductors of insulated cables
- IEC 60229 Tests on extruded oversheaths which have a special protective function
- IEC 60287 Electric cables - calculation of the current rating
- IEC 60840 Power cables with extruded insulation and their accessories

5.1.2 Submarine cables

Low losses

To avoid ferromagnetic losses AC submarine cables need non-magnetic material for the wire armor, thus copper or aluminum alloy or non-magnetic stainless steel wires are used. For DC cables, there are no magnetic losses, hence galvanized steel wires, can be used for the tensile armor.

Deep sea waters

HVDC Light® cables are suitable for deep water for the following reasons:

- Polymeric insulation is mechanically robust.
- HVDC cables are generally less heavy than AC cables for the same transferred power, which gives lower tensile force during laying of the cables.
- It is advantageous to use galvanized steel wires for tensile armor, because galvanized steel wire has better tensile properties than most non-magnetic materials that can be used.

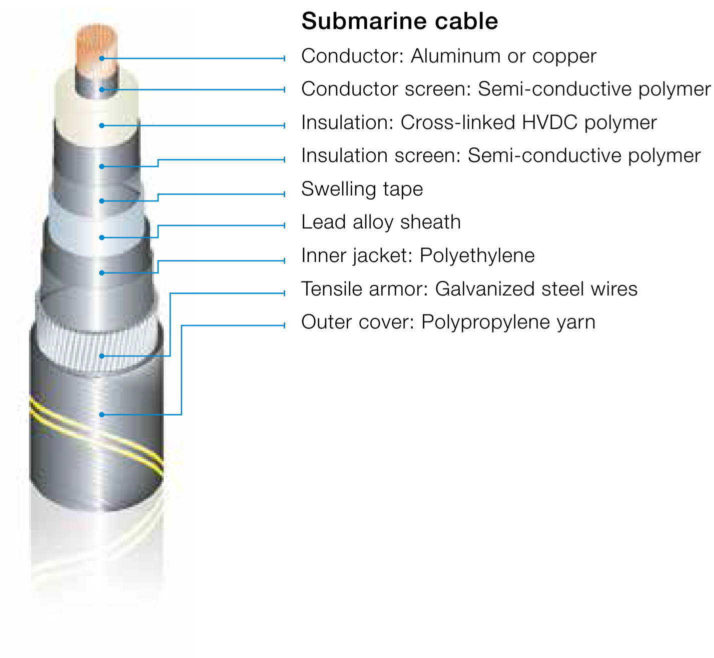
Laying and repair

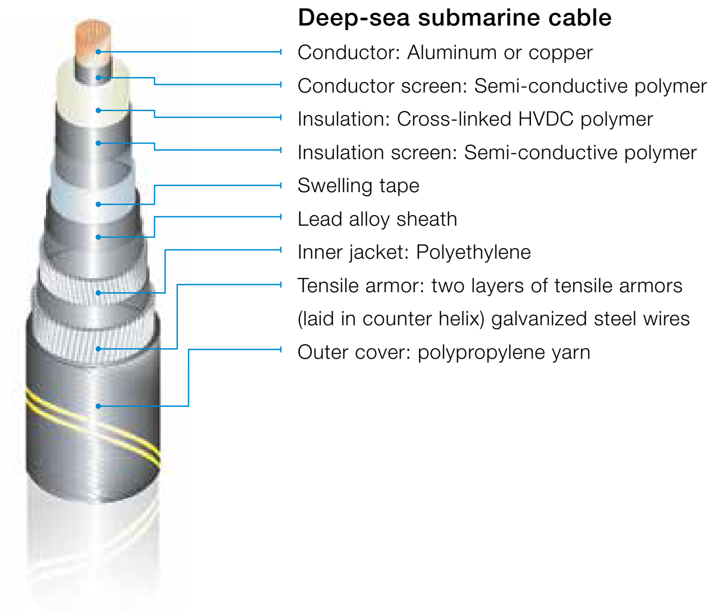
HVDC Light® cables are very flexible with respect to various installation methods, due to their robust and flexible insulation material. Should a repair be required, the availability of suitable cable ships is useful.

- The cable can be coiled on a cable laying ship (except for cables with double cross laid armor for large depths). The ability to coil the cable makes it possible to lay it from small barges and transport it by cargo ship without the need of cable turntables.
- It is possible in most cases to lay the two cables of the bipole close to each other (e.g. by bundling the cables) in one common trench.
- The bending radius of the polymeric insulated HVDC Light® cable is smaller compared with paper-insulated cables, which makes it possible to use cable-laying ships with a smaller pay-off wheel, and also smaller trenching equipment.

Good resistance when installed

Particularly when compared with paper-oil insulated cables, HVDC Light® cables can resist repeated bending without damaging the insulation. This is of critical importance for cables hanging in spans over an uneven sea bed.





5.1.3 Land cables

Permitting

In many cases it is easier to get right of way for underground cables, compared with overhead transmission lines. The main reasons are:

– Lower visual impact
– Narrower required right-of-ways

Handling

HVDC Light® cables have many advantages compared with other cable types, such as:

– HVDC Light® cables have smaller bending radius compared with paper insulated cables. This makes it possible to use smaller cable drums for transportation, and makes it possible to use compact installation, e.g. on offshore platforms. The smaller bending radius also makes it possible to go around obstacles such as rocks, etc.
– HVDC Light® cables are possible to handle at lower temperatures compared with paper insulated cables.

Minimum bending radius for standard designs

During installation, the bending radius should exceed 18 x De. When the cable is installed (no force applied to the cable), the bending radius must exceed 12 x De. De is the external diameter of the cable.

Maximum pulling forces

When the pulling nose is attached to the conductor, the following tensile forces should not be exceeded:

– 70 N/mm² for Cu conductors
– 40 N/mm² for Al conductors

Jointing

HVDC Light® cable joints are usually installed inside a portable jointing house, which is placed in the joint bay. This prebuilt jointing house provides adequate light, dust control, clean work surfaces and cable stands to place the joint within comfortable reach of the cable jointers. A crew of two cable jointers usually works together as a team. A joint crew can complete one of these joints in one working day.

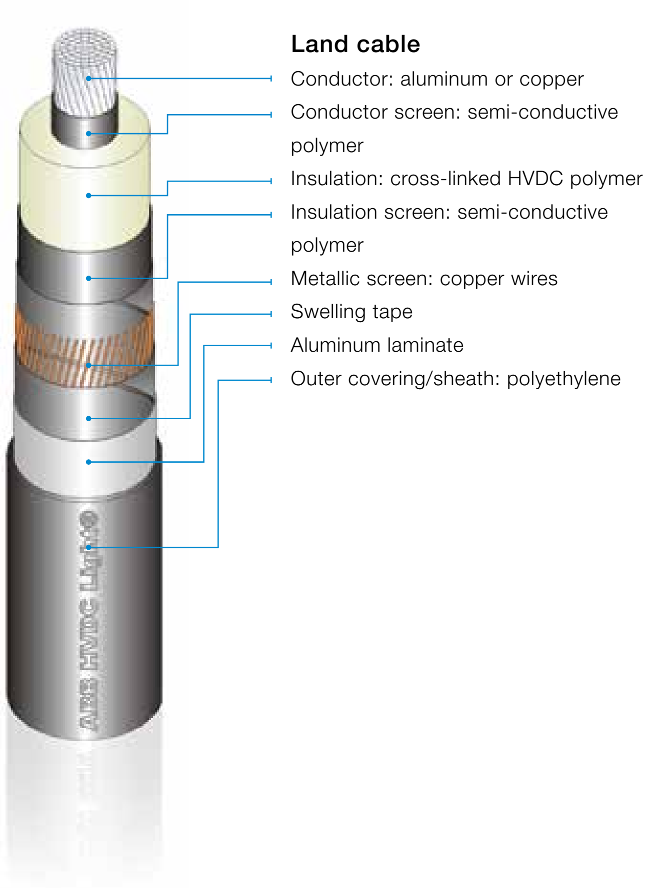
No magnetic fields of power frequency

There is no power frequency magnetic field from a DC cable; there is only a static magnetic field, similar to the earth's magnetic field. Recommended levels of static magnetic field strength are significantly higher than for power frequency fields (from AC power lines), since there is no induction effect, and the magnetic fields are similar to that of the earth itself.

A conventional monopolar HVDC cable scheme with a current of 1,000 amps gives a magnetic field of 20 microtesla magnitude at a distance of 10 meters. This is approximately half the magnitude of the earth's natural magnetic field. With HVDC Light® cables, the magnetic field is reduced to less than 0.2 microtesla, which is less than one percent of natural magnetism.

Cable drums

Land cables are typically transported on cable drums. Steel drums with outer diameters up to 4.5 m are available, but transport restrictions have to be considered. Special low-loading trailers and permits from traffic authorities may be required, depending on local regulations and conditions. Special wooden drums with a larger barrel diameter or larger width (up to 2.5 m) are also available, if needed.



5.1.4 Installation

Submarine cables

The cable can be installed on all types of seabed, including sand, sediment, rocks and reefs. For protection against anchors and fishing gear, the cable can be buried by various methods, or can be protected by covers. The cables can be laid either separately or close together, and protection can be provided by means of water jetting or ploughing, either simultaneously with or after the cable laying.

Submarine cable installation may include the following items of work:

- Route survey
- Calculation of tensile forces
- Installation plans
- Cable laying vessels
- Marine works
- Burial of the cable
- Equipment for cable pulling
- Directional drilling on shore
- Post-installation testing

Land cables

The installation of cable systems consists mainly of cable pulling, clamping of cable and accessories as well as mounting of accessories. The installation design is an important part of the cable system design. ABB certified erectors perform the high quality work necessary for the reliable operation of a cable system during its lifetime. ABB has long and good experience of traditional installation technologies including direct burial, duct, shaft, trough and tunnel, but also trench-less technologies including directional drilling, pipe jacking and others.

5.1.5 Repair

Fault Location

It is important to perform a fairly fast prelocation of a fault to aid repair planning. The converter protections identify the cable that is faulty. If possible, prelocation could start with an analysis of the records in the converter stations in order to roughly estimate the location of the fault.

Prelocation of fault with pulse echo meter or fault location bridge

A fault in the HVDC cable can be prelocated with an impulse generator (Thumper) and a Time Domain Reflection meter (TDR). The thumper creates high voltage impulses, and the time required for the pulse to travel to and from the cable is measured with the TDR. A fault in the HVDC cable can also be located with a fault location bridge. The fault location bridge is a high-precision instrument based on the Wheatstone measuring bridge, and a measurement with this device should give approximately the same distance to the fault as the TDR.

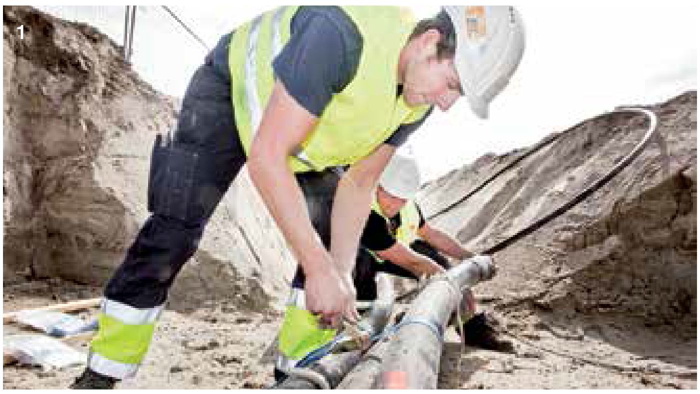
Accurate location of a fault

The principle of this method is to use a powerful thumper to create a flashover at the fault. The sound from the flashover and/or the magnetic field from the pulse is picked up with microphones or with spikes connected to a receiver.

Repair time

An HVDC Light® cable repair on a land cable should take less than a week, even if a section has to be removed and replaced in a duct system. A directly buried cable can easily be opened and repaired in a short time by installing a new section of cable and two joints. The basic requirement in this case would be to have some spare joints, spare cable and jointing tools available in the customers' stores.

1 Typical cable laying and trenching operation | 2 Coiled cable on small cable laying barge.



5.1.6 Accessories

The only accessories required for HVDC Light® cable systems are cable joints and terminations.

Cable joints

Joints for HVDC Light® are based on field molding or prefabricated joint techniques.

Cable terminations

Terminations are used to connect the cables to the HVDC converters. The terminations are mounted indoors in the converter stations. The termination is made up of several prefabricated parts.

The field molding method uses a mini-process to restore the insulation, and creates a joint with the same diameter as the cable. Prefabricated joints are used to connect the cables. The design involves a screwed conductor connector and a prefabricated rubber joint body. The body has a built-in semi-conductive deflector and a non-linear resistive field control. The one piece design of the joint body reduces the amount of sensitive interfaces and simplifies pretesting of the joint bodies.

5.1.7 Auxiliary equipment

Other auxiliary equipment may be used for the cable system, for example:

- Cable temperature sensing systems
- Forced cooling systems

5.1.8 Environmentally sound

The cable does not contain oil or other toxic components. It does not harm living marine organisms. Due to its design, the cable does not emit electrical fields. The magnetic field from the cable is negligible. The cable can be recovered and recycled at the end of its useful life.

1 **HVDC Light cable joint 320 kV**

1

Annex

HVDC Light® cable data

Capability, losses etc for submarine and land cables installed in tropical and moderate climate zones are shown below.

Submarine cables

Tropical climate, submarine cables with copper conductor

Area	Ampacity		±80 kV bipole				±150 kV bipole				±320 kV bipole			
Con-ductor	Close laying	Spaced laying	Close laying	Spaced laying	Weight per cable	Diam. over cable	Close laying	Spaced laying	Weight per cable	Diam. over cable	Close laying	Spaced laying	Weight per cable	Diam. over cable
mm²	Amps	Amps	MW	MW	kg/m	mm	MW	MW	kg/m	mm	MW	MW	kg/m	mm
95	282	338	45	54	4,7	42	85	101	8,5	60	180	216	15	90
120	323	387	52	62	5,5	44	97	116	9,4	61	207	248	16	91
150	363	436	58	70	6,7	47	109	131	10	63	232	279	17	93
185	411	496	66	79	7,4	49	123	149	11	64	263	317	18	95
240	478	580	76	93	8,4	52	143	174	12	67	306	371	20	99
300	544	662	87	106	9,4	56	163	199	13	69	348	424	22	102
400	626	765	100	122	11	61	188	230	16	75	401	490	24	105
500	722	887	116	142	13	66	217	266	18	78	462	568	26	108
630	835	1030	134	165	15	71	251	309	21	83	534	659	30	114
800	960	1187	154	190	17	76	288	356	24	88	614	760	33	118
1000	1092	1355	175	217	21	81	328	407	26	96	699	867	37	122
1200	1188	1474	190	236	24	85	356	442	29	100	760	943	40	126
1400	1297	1614	208	258	27	89	389	484	32	103	830	1033	43	130
1600	1397	1745	224	279	30	92	419	524	35	107	894	1117	47	133
1800	1490	1860	238	298	32	96	447	558	38	110	954	1190	50	137
2000	1589	1987	254	318	35	99	477	596	41	113	1017	1272	53	140
2200	1676	2086	268	334	40	103	503	626	45	118	1073	1335	58	145
2400	1764	2198	282	352	42	106	529	659	48	121	1129	1407	61	148

Sea soil: Temperature 28 degrees C, burial 1.0 meter, thermal resistivity 1.2 K × W /m
Cable: Copper conductor, HVDC polymer insulation, steel wire armor

Bipolar power transmission is P = 2×U×I×10-3 MW
Bipolar transmission losses are P = 2×R×10-3×I2 W/m
Voltage drop at 100% load is U = R×I V/km

Area	Resistance	Voltage drop		Losses at 50percent		Losses at 100percent	
Copper Conductor	per phase 20 deg.C	Close laying	Spaced laying	Close laying	Spaced laying	Close laying	Spaced laying
mm²	ohm/km	V/km	V/km	W/m	W/m	W/m	W/m
95	0,193	65	78	8	12	37	53
120	0,153	59	71	9	12	38	55
150	0,124	54	65	9	13	39	57
185	0,0991	49	59	9	13	40	59
240	0,0754	43	52	9	14	41	60
300	0,0601	39	48	9	14	42	64
400	0,0470	35	43	10	15	44	66
500	0,0366	32	39	10	15	46	69
630	0,0283	28	35	11	16	47	72
800	0,0221	25	31	11	17	48	74
1000	0,0176	23	29	11	17	50	79
1200	0,0151	21	27	11	18	50	80
1400	0,0126	20	24	11	18	52	77
1600	0,0113	19	24	12	18	53	84
1800	0,0098	17	22	12	18	51	82
2000	0,0090	17	21	12	19	54	83
2200	0,0080	16	20	12	19	54	83
2400	0,0073	15	19	12	19	53	84

Moderate climate, submarine cables with copper conductor

Area	Ampacity		±80 kV bipole				±150 kV bipole				±320 kV bipole			
Con-ductor	Close laying	Spaced laying	Close laying	Spaced laying	Weight per cable	Diam. over cable	Close laying	Spaced laying	Weight per cable	Diam. over cable	Close laying	Spaced laying	Weight per cable	Diam. over cable
mm²	Amps	Amps	MW	MW	kg/m	mm	MW	MW	kg/m	mm	MW	MW	kg/m	mm
95	343	404	55	65	4,7	42	103	121	8,5	60	220	259	15	90
120	392	463	63	74	5,5	44	118	139	9,4	61	251	296	16	91
150	441	523	71	84	6,7	47	132	157	10	63	282	335	17	93
185	500	596	80	95	7,4	49	150	179	11	64	320	381	18	95
240	583	697	93	112	8,4	52	175	209	12	67	373	446	20	99
300	662	797	106	128	9,4	56	199	239	13	69	424	510	22	102
400	765	922	122	148	11	61	230	277	16	75	490	590	24	105
500	883	1072	141	172	13	66	265	322	18	78	565	686	26	108
630	1023	1246	164	199	15	71	307	374	21	83	655	797	30	114
800	1175	1438	188	230	17	76	353	431	24	88	752	920	33	118
1000	1335	1644	214	263	21	81	401	493	26	96	854	1052	37	122
1200	1458	1791	233	287	24	85	437	537	29	100	933	1146	40	126
1400	1594	1962	255	314	27	89	478	589	32	103	1020	1256	43	130
1600	1720	2123	275	340	30	92	516	637	35	107	1101	1359	47	133
1800	1830	2265	293	362	32	96	549	680	38	110	1171	1450	50	137
2000	1953	2407	312	385	35	99	586	722	41	113	1250	1540	53	140
2200	2062	2540	330	406	40	103	619	762	45	118	1320	1626	58	145
2400	2170	2678	347	428	42	106	651	803	48	121	1389	1714	61	148

Sea soil: Temperature 15 degrees C, burial 1.0 meter, thermal resistivity 1.0 K × W /m
Cable: Copper conductor, HVDC polymer insulation, steel wire armor

Bipolar power transmission is P = 2×U×I×10-3 MW
Bipolar transmission losses are P = 2×R×10-3×I2 W/m
Voltage drop at 100% load is U = R×I V/km

Area	Resistance	Voltage drop		Losses at 50percent		Losses at 100percent	
Copper Conductor	per phase 20 deg.C	Close laying	Spaced laying	Close laying	Spaced laying	Close laying	Spaced laying
mm²	ohm/km	V/km	V/km	W/m	W/m	W/m	W/m
95	0,193	79	93	12	16	54	75
120	0,153	72	85	12	17	56	79
150	0,124	65	78	12	17	57	82
185	0,0991	59	71	13	18	59	85
240	0,0754	53	63	13	19	62	88
300	0,0601	48	57	14	20	64	91
400	0,0470	43	52	14	21	66	96
500	0,0366	39	47	15	22	69	101
630	0,0283	35	42	15	23	72	105
800	0,0221	31	38	16	23	73	109
1000	0,0176	28	35	16	24	75	115
1200	0,0151	26	32	16	25	76	115
1400	0,0126	24	30	16	25	77	118
1600	0,0113	23	29	17	26	79	123
1800	0,0098	21	27	17	26	77	122
2000	0,0090	21	26	18	27	82	125
2200	0,0080	20	24	17	26	82	122
2400	0,0073	19	23	18	27	82	123

Land cables

Tropical climate, land cables with aluminum conductor
For higher transmission capacity, see submarine cables with copper conductor

Area	Ampacity		±80 kV bipole				±150 kV bipole				±320 kV bipole			
Con-ductor	Close laying	Spaced laying	Close laying	Spaced laying	Weight per cable	Diam. over cable	Close laying	Spaced laying	Weight per cable	Diam. over cable	Close laying	Spaced laying	Weight per cable	Diam. over cable
mm²	Amps	Amps	MW	MW	kg/m	mm	MW	MW	kg/m	mm	MW	MW	kg/m	mm
95	211	258	34	41	1,2	33	-	-	-	-	-	-	-	-
120	240	298	38	48	1,3	34	-	-	-	-	-	-	-	-
150	269	332	43	53	1,5	36	81	100	2	50	-	-	-	-
185	305	378	49	60	1,6	38	92	113	3	52	-	-	-	-
240	351	439	56	70	1,9	40	105	132	3	54	225	281	5	80
300	400	503	64	80	2,1	43	120	151	3	57	256	322	6	82
400	456	581	73	93	3	46	137	174	4	60	292	372	6	86
500	536	672	86	108	3	50	161	202	4	63	343	430	7	89
630	591	744	95	119	3	53	177	223	5	67	378	476	8	93
800	711	898	114	144	4	57	213	269	5	71	455	575	8	97
1000	811	1026	130	164	5	61	243	308	6	75	519	657	9	101
1200	888	1123	142	180	6	65	266	337	7	79	568	719	10	105
1400	980	1242	157	199	6	69	294	373	8	83	627	795	11	108
1600	1044	1326	167	212	7	72	313	398	9	86	668	849	12	112
1800	1129	1434	181	229	8	75	339	430	9	89	723	918	13	115
2000	1198	1524	192	244	8	78	359	457	10	92	767	975	14	118
2200	1265	1600	202	256	9	81	380	480	11	95	810	1024	15	121
2400	1330	1681	213	269	10	84	399	504	11	98	851	1076	16	123

Sea soil: Temperature 28 degrees C, Burial 1.0 meter, Thermal resistivity 1.2 K × W /m
Cable: Aluminum conductor, HVDC polymer insulation, Copper wire screen

Bipolar power transmission is P = 2×U×I×10-3 MW
Bipolar transmission losses are P = 2×R×10-3×I2 W/m
Voltage drop at 100% load is U = R×I V/km

Area	Resistance	Voltage drop		Losses at 50percent		Losses at 100percent	
Aluminium Conductor	per phase 20 deg.C	Close laying	Spaced laying	Close laying	Spaced laying	Close laying	Spaced laying
mm²	ohm/km	V/km	V/km	W/m	W/m	W/m	W/m
95	0,32	81	99	8	11	34	51
120	0,253	73	90	8	12	35	54
150	0,206	66	82	8	12	36	54
185	0,1640	60	74	8	13	37	56
240	0,1250	52	66	8	13	37	58
300	0,1000	48	60	9	14	38	60
400	0,0778	42	54	9	14	38	63
500	0,0605	39	49	9	15	42	66
630	0,0469	33	42	9	14	39	62
800	0,0367	31	39	10	16	44	70
1000	0,0291	28	36	10	16	45	74
1200	0,0247	26	33	10	17	46	74
1400	0,0208	24	31	11	17	47	77
1600	0,0186	23	30	11	17	48	80
1800	0,0162	22	28	11	18	50	80
2000	0,0149	21	27	11	19	50	82
2200	0,0132	20	25	11	18	51	80
2400	0,0121	19	24	11	18	51	81

Moderate climate, land cables with aluminum conductor
For higher transmission capacity, see submarine cables with copper conductor

Area	Ampacity		±80 kV bipole				±150 kV bipole				±320 kV bipole			
Con-ductor	Close laying	Spaced laying	Close laying	Spaced laying	Weight per cable	Diam. over cable	Close laying	Spaced laying	Weight per cable	Diam. over cable	Close laying	Spaced laying	Weight per cable	Diam. over cable
mm²	Amps	Amps	MW	MW	kg/m	mm	MW	MW	kg/m	mm	MW	MW	kg/m	mm
95	258	310	41	50	1,2	33	-	-	-	-	-	-	-	-
120	294	357	47	57	1,3	34	-	-	-	-	-	-	-	-
150	330	402	53	64	1,5	36	99	121	2	50	-	-	-	-
185	374	458	60	73	1,6	38	112	137	3	52	-	-	-	-
240	432	533	69	85	1,9	40	130	160	3	54	276	341	5	80
300	492	611	79	98	2,1	43	148	183	3	57	315	391	6	82
400	565	705	90	113	3	46	170	212	4	60	362	451	6	86
500	659	816	105	131	3	50	198	245	4	63	422	522	7	89
630	727	964	116	154	3	53	218	289	5	67	465	617	8	93
800	877	1094	140	175	4	57	263	328	5	71	561	700	8	97
1000	1001	1252	160	200	5	61	300	376	6	75	641	801	9	101
1200	1096	1371	175	219	6	65	329	411	7	79	701	877	10	105
1400	1211	1517	194	243	6	69	363	455	8	83	775	971	11	108
1600	1291	1621	207	259	7	72	387	486	9	86	826	1037	12	112
1800	1395	1752	223	280	8	75	419	526	9	89	893	1121	13	115
2000	1482	1866	237	299	8	78	445	560	10	92	948	1194	14	118
2200	1571	1963	251	314	9	81	471	589	11	95	1005	1256	15	121
2400	1652	2066	264	331	10	84	496	620	11	98	1057	1322	16	123

Sea soil: Temperature 15 degrees C, Burial 1.0 meter, Thermal resistivity 1.0 K × W /m
Cable: Aluminum conductor, HVDC polymer insulation, Copper wire screen

Bipolar power transmission is P = 2×U×I×10-3 MW
Bipolar transmission losses are P = 2×R×10-3×I2 W/m
Voltage drop at 100% load is U = R×I V/km

Area	Resistance	Voltage drop		Losses at 50percent		Losses at 100percent	
Aluminium Conductor	per phase 20 deg.C	Close laying	Spaced laying	Close laying	Spaced laying	Close laying	Spaced laying
mm²	ohm/km	V/km	V/km	W/m	W/m	W/m	W/m
95	0,32	99	119	11	16	51	74
120	0,253	89	108	11	17	52	77
150	0,206	81	99	12	17	53	80
185	0,1640	73	90	12	18	55	82
240	0,1250	65	80	12	18	56	85
300	0,1000	59	73	12	19	58	89
400	0,0778	53	66	13	20	60	93
500	0,0605	48	59	13	21	63	96
630	0,0469	41	54	13	22	60	104
800	0,0367	39	48	14	23	68	105
1000	0,0291	35	44	15	23	70	110
1200	0,0247	32	41	15	24	70	112
1400	0,0208	30	38	16	25	73	115
1600	0,0186	29	36	16	25	75	117
1800	0,0162	27	34	16	26	75	119
2000	0,0149	26	33	17	27	77	123
2200	0,0132	25	31	17	26	79	122
2400	0,0121	24	30	17	27	79	124

Testing

Tests are performed according to combinations of relevant parts from

- Cigré recommendations for mechanical testing of submarine cables published in Electra 171
- IEC 60840, Power cables with extruded insulation and their accessories
- Cigré "Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to 250 kV", published in Cigré technical brochure Ref No 219

HVDC Light® Cable test voltages

U_0 kV	U_T kV	U_{TP1} kV	SIPL kV	$U_{P2,S}$ kV	$U_{P2,O}$ kV
80	148	116	143	165	92
150	278	217	275	320	175
320	592	464	578	665	375
200	370	290	359	413	213

Definitions

U_0 Rated DC voltage.

U_T Load cycle test voltage = $1.85U_0$ at test at works and Factory Acceptance Test.

U_{TP1} Polarity reversal test voltage = $1.45U_0$, also for post-installation testing.

$U_{P2,S}$ Same polarity switching impulse voltage > 1.15SIPL.

$U_{P2,O}$ Opposite polarity switching impulse voltage

Peak values of U_{P1}, $U_{P2,S}$ and $U_{P2,O}$ are defined as maximum voltages to ground when a suitable charge is transferred from the impulse generator to the cable.

Type test

The table below summarizes the status of type-tested HVDC Light® cable systems (up to year 2007). If type tests have already been performed, they need not to be repeated for cables within the scope of approval as defined by Cigré.

Voltage U_0 [kV]	Conductor area [mm²]	Number of performed type tests
80	95	2
80	300-340	5
80	630	2
150	95	4
150	1000-1600	11
150	2000-2300	3
200	1650-2210	2
320	1200	2
	Total	31

The electrical type tests are composed of following test items:

- Mechanical tests: Bending of land cables as per IEC 60840. Submarine cables as per Cigré Recommendations, ELECTRA No. 171 – clause 3.2.
- Load Cycle Test
- Superimposed impulse voltage test: Switching Surge Withstand Test, at $U_{P2,S}$ and $U_{P2,O}$

Routine and sample test

Routine testing will be performed on each manufactured length of cable.

- Voltage test, U_T during 15 minutes.

For land cables also:

- DC-testing of non-metallic sheath, according to IEC 60229.

The following sample tests are performed (generally on one length from each manufacturing series):

- Conductor examination
- Measurement of electrical resistance of the conductor
- Measurement of thickness of insulation and non-metallic sheath
- Measurement of diameters on complete cable (for information)
- Hot set test of insulation material

Post-installation test

- Voltage test, U_{TP1} during 15 min.

For land cables also:
DC-testing on non-metallic sheath, according to IEC 60229