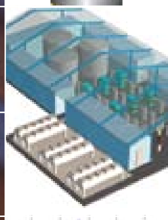
It's time to connect

New revised edition

- Technical description of HVDC Light® technology

Table of Contents



After the huge blackout in August 2003, a federal order allowed the first use of the Cross Sound Cable HVDC Light® Interconnector. The cable interconnection made a major contribution to getting Long Island out of the dark and restoring power to hundreds of thousands of customers across Long Island. LIPA Chairman Richard Kessel heralded Cross Sound Cable as a “national symbol of how we need to enhance our infrastructure”.

Proven technology in new applications

Our need for energy as a naturally integrated part of society is increasing, and electricity is increasing its share of the total energy used. It is truer than ever that electricity is a base for building a modern society, but also a principal tool for increasing well-being in developing countries. As a result, greater focus is directed at how the electricity is generated and distributed. In addition, society requests less environmental impact from transmission and generation along with higher reliability and availability. To combine these goals there is a need for new technologies for transmitting and distributing electrical energy.

In this book we present our response to these needs, the HVDC Light® technique. HVDC Light® makes invisible underground transmission systems technically and economically viable over long distances. The technology is also well suited for a number of applications such as power supply to offshore platforms, connecting offshore wind farms, improving grid reliability, city infeed and powering islands. In these applications, specific characteristics of the technology such as compact and light weight design, short installation and commissioning time, low operation and maintenance costs and superior control of voltages, active and reactive power can be utilized.

It is my true belief that the HVDC Light® technique will actively contribute to the development of transmission systems, in line with the requests given from our society.

March 2008

Per Haugland

Per Haugland
Senior Vice President
Grid Systems

1 Introduction

1.0 Development of HVDC technology – historical background

Direct current was the first type of transmission system used in the very early days of electrical engineering. Even though the AC transmission system later on came to play a very important role, the development of DC transmission has always continued. In the 1930s, the striving for more and more power again raised the interest in high voltage DC transmission as an efficient tool for the transmission of large power volumes from remote localities. This initiated the development of mercury arc converters, and more than 20 years later, in 1954, the world's first commercial HVDC link based on mercury arc converters went into service between the Swedish mainland and the island of Gotland. This was followed by many small and larger mercury arc schemes around the world. Around 20 years later, in the early 1970s, the thyristor semiconductor started to replace the mercury converters.

ABB has delivered more than 60 HVDC projects around the world providing more than 48,000 MW capacity. The largest bipole delivered is 3150 MW.

1.1 What is HVDC Light®?

HVDC Light® is the successful and environmentally-friendly way to design a power transmission system for a submarine cable, an underground cable, using over head lines or as a back-to-back transmission.

HVDC Light® is HVDC technology based on voltage source converters (VSCs). Combined with extruded DC cables, overhead lines or back-to-back, power ratings from a few tenths of megawatts up to over 1,000 MW are available. HVDC Light® converters are based on insulated gate bipolar transistors (IGBTs) and operate with high frequency pulse width modulation in order to achieve high speed and, as a consequence, small filters and independent control of both active and reactive power.

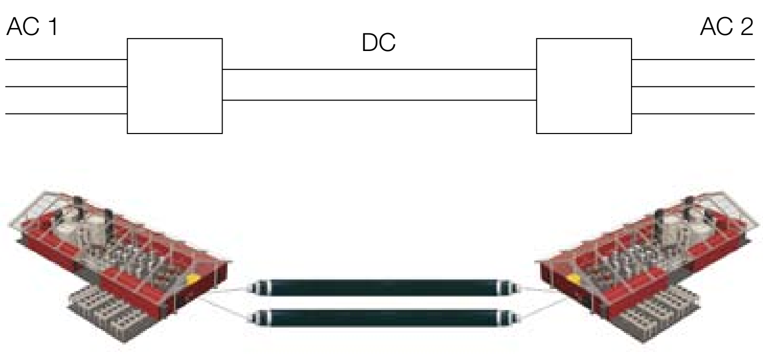
HVDC Light® cables have extruded polymer insulation. Their strength and flexibility make them well suited for severe installation conditions, both underground as a land cable and as a submarine cable.

The converter station designs are based on voltage source converters employing state-of-the-art turn on/turn off IGBT power semiconductors.

HVDC Light® has the capability to rapidly control both active and reactive power independently of each other, to keep the voltage and frequency stable. This gives total flexibility regarding the location of the converters in the AC system, since the requirements for the short-circuit capacity of the connected AC network are low (SCR down to zero).

The HVDC Light® design is based on a modular concept. For DC voltages up to ± 150 kV, most of the equipment is installed in enclosures at the factory. For the highest DC voltages, the equipment is installed in buildings. The required sizes of the site areas for the converter stations are also small. All equipment except the power transformers is indoors.

Well-proven and equipment tested at the factory make installation and commissioning quick and efficient.



Installation of an HVDC Light® station

A pair of HVDC Light® land cables

The stations are designed to be unmanned. They can be operated remotely or could even be automatic, based on the needs of the interconnected AC networks. Maintenance requirements are determined mainly by conventional equipment such as the AC breakers, cooling system, etc.

The cable system is supplied complete with cables, accessories and installation services. The cables are operated in bipolar mode, one cable with positive polarity and one cable with negative polarity.

The cables have polymeric insulating material, which is very strong and robust.

This strength and flexibility make the HVDC Light® cables perfect for severe installation conditions:
- The submarine cables can be laid in deeper waters and on rough bottoms.
- The land cables can be installed less expensively with the ploughing technique.

The environmental benefits are:
- Magnetic fields are eliminated since HVDC Light® cables are laid in pairs with DC currents in opposite directions. The magnetic field from a DC cable is not pulsating but static - just as the earth's natural magnetic field. The strength of the field is 1/10th of the earth's natural magnetic field one meter above the ground immediately above the cable. Thus there are no relevant magnetic fields when using HVDC Light® cables.
- Risk of oil spill, as in paper-oil insulated cables, is eliminated.
- The cable insulation is an environmentally friendly recyclable PE based material.
- The cable metals can be recycled.
- Low smoke generation and no halogen is emitted if burning.

Power transmission via cables gives
- no visual impact
- no ground current
- no relevant electromagnetic fields.

1.2 Reference projects

1.2.1 Gotland HVDC Light®, Sweden

- Client need
An environmentally-friendly way of connecting wind power to the load centre of the grid and high functional requirements on performance in the network.

- ABB response
50 MW / ± 25 MVar HVDC Light® converters and 140 km (2 x 70 km) ± 80 kV HVDC Light® land cables. Project commissioned 1999.

- Summary – Gotland HVDC Light®
For the Gotland scheme it was possible to develop and implement practical operational measures thanks mainly to the experienced flexibility of HVDC Light®. Essential aspects to consider were:

• Flicker problems were eliminated with the installation of HVDC Light®. Apparently, the transient voltage control prevents the AC voltage from locking to the flicker.

• Transient phenomena at which faults were dominant. This was the most significant problem.

The parallel connection of HVDC with the AC grid and the weak grid in one station make the response time very important. Even the asynchronous generator behavior has an impact during AC faults. It has been shown that a standard voltage controller cannot be used to manage these situations. The parameter settings have to consider that the system must not be too fast in normal operation, and that it has to act rapidly when something happens, which has been easily accomplished with HVDC Light®.

Studies of fault events in the AC system have shown considerable improvements in behavior both during the faults and at recovery, including improved stability.

• Stability in the system.

• Power flows, reactive power demands, as well as voltage levels in the system. To meet the output power variation from the wind turbines, an automatic power flow control system has been developed to minimize the losses and avoid overload on the AC lines. In normal conditions the overall SCADA system determines the set points for active and reactive power to minimize the total losses in the whole system. This function is important, so that there is no need for the operators to be on line and to carry out the control manually.

Overall experiences are that the control of the power flow from the converters makes the AC grid easier to supervise than a conventional AC network, and the power variations do not stress the AC grid as much as in normal networks. Voltage quality has also improved with the increased wind power production. Sensitive customers, such as big industrial companies, now suffer less from disturbances due to voltage dips and other voltage quality imperfections. Even if the network cannot manage all AC faults, the average behavior over a year points to much better voltage quality.

1.2.2 Directlink, Australia

- Client need
Environmentally-friendly power link for power trading between two states in Australia.

- ABB response
3 x 60 MW HVDC Light® converters and 390 km (6 x 65 km) ± 80kV HVDC Light® land cables.
Project commissioned 2000.

- Summary – Directlink
Directlink is a 180 MVA HVDC Light® project, consisting of three parallel 60 MVA transmission links that connect the regional electricity markets of New South Wales and Queensland. Directlink is a non-regulated project, operating as a generator by delivering energy to the highest value regional market.

The Directlink project features three innovations which minimize its environmental, aesthetic and commercial impact: the cable is buried underground for the entire 65 km; it is an entrepreneurial project that was paid for by its developers, and the flow of energy over HVDC Light® facilities can be precisely defined and controlled. The voltage source converter terminals can act independently of each other to provide ancillary services (such as VAR support) in the weak networks to which Directlink connects.

Experience with the operation of Directlink with three parallel links started in the middle of 2000 and confirms the expected excellent behavior of the controllability of the transmission.

HVDC Light® station in Näs, Gotland

1.2.3 Tjæreborg, Denmark

- Client need

A small-scale HVDC Light® system to be used for testing optimal transmission from wind power generation.

- ABB response

8 MVA HVDC Light® converters and 9 km (2 x 4.5 km) ± 9 kV HVDC Light® land cables. Project commissioned 2000.

- Summary – Tjæreborg HVDC Light®

The purpose of the Tjæreborg HVDC project was to investigate how the controllability of HVDC Light® could be used for optimal exploitation of the wind energy by using the converter to provide a collective variable frequency to the wind turbines. The Tjæreborg wind farm can either be connected via the AC transmission only, or via the DC transmission only, or via the AC and the DC cables in parallel. The HVDC Light® control system is designed to connect via the AC transmission automatically if the wind power production is below 500 kW, and via the DC cables if the power is higher than 700 kW.

Experience has been gained of the successful use of HVDC Light® for:

• Starting and stopping the wind turbines at low and high wind speeds.

• Smooth automatic switching between the AC and DC transmission by automatically synchronizing the wind turbines to the AC grid.

• Start against black network. This was tested, as an isolated AC grid, e.g. an islanded wind farm has to be energized from the DC transmission.

• With a connected wind turbine generator, the frequency was varied between 46 and 50 Hz. A separate test without connected wind turbines demonstrated that the HVDC Light® inverter frequency could be varied between 30 Hz and 65 Hz without any problems.

The Tjæreborg HVDC Light® station

Directlink HVDC Light® station 3 x 60 MW

1.2.4 Eagle Pass, US

- Client need
Stabilization of AC voltage and possibility to import power from Mexico during emergencies.

- ABB response
36 MVA HVDC Light® back-to-back converters. Project commissioned 2000.

- Summary – Eagle Pass
HVDC Light® back-to-back was chosen since other alternatives would have been more expensive, and building a new AC line would have faced the added impediment of having to overcome difficulties in acquiring the necessary rights of way. Furthermore, if an HVDC back-to-back based on conventional technology had been considered, there were concerns that such a solution might not provide the necessary level of reliability because of the weakness of the AC system on the U.S. side of the border.

To mitigate possible voltage instability and, at the same time, to allow power exchange in either direction between the U.S. and Mexico without first having to disrupt service to distribution system customers, an HVDC Light® back-to-back rated at 36 MVA at 138 kV was installed and commissioned.

1.2.5 Cross Sound Cable, US

- Client need
Environmentally-friendly controllable power transmission to Long Island.

- ABB response
330 MW MW HVDC Light® converters and 84 km (2 x 42 km) ±150 kV HVDC Light® submarine cables. Project commissioned 2002.

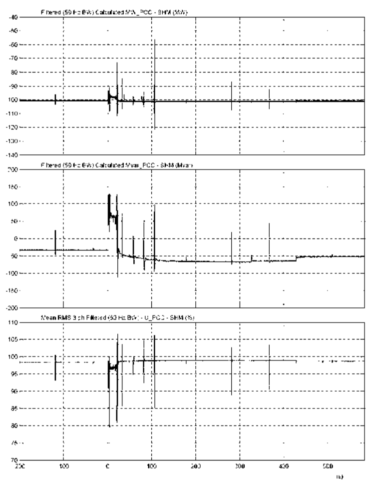
The two HVDC Light® power cables and the multi-fiber optic cable were laid bundled together to minimize the impact on the sea bottom and to protect oysters, scallops and other living species. The cables were buried six feet into the sea floor to give protection against fishing gear and ships' anchors. The submarine Fiber Optic cable is furnished with 192 fibers.

- Summary – Cross Sound Cable
The Cross Sound Cable project is a 42 km HVDC Light® transmission between New Haven, Connecticut and Shoreham on Long Island outside New York. It provides the transmission of electric energy to Long Island. The rating is 330 MW with the possibility of both local and remote control.

HVDC Light® station at Shoreham

Testing of the Cross Sound Cable project was completed in August 2002. The big blackout in the north-eastern states happened on August 14 2003, and the Cross Sound transmission became an important power supply route to Long Island when restoring the network during the blackout.

Some hours after the blackout, a federal order was given to start emergency operation. In addition to providing power to Long Island, the AC voltage control provided by the link of both the Long Island and the Connecticut networks showed that it could keep the AC voltages constant. During the thunderstorms that occurred before the networks were completely restored, several +100 to –70 Mvar swings were noticed over 20 seconds. AC voltage was kept constant. The transmission remained in emergency operation during the fall of 2003. The owner has concluded that the cable interconnection made a major contribution to getting Long Island out of the dark and restoring power to hundreds of thousands of customers across Long Island.



Steady-State 100 MW CT —> LI during thunderstorm. ACVC APC SHM. Measurement in Shoreham Converter Station (DASH-18) Sunday 17 August 2003 – 18:48:00.000

1.2.6 MurrayLink, Australia

- Client need
Environmentally-friendly power link for power trading between two states in Australia.

- ABB response
200 MW HVDC Light® converters and 360 km (2 x 180 km) ±150 kV HVDC Light® land cables. Project commissioned 2002.

- Summary – MurrayLink
MurrayLink is a 180 km underground 200 MW transmission system between Red Cliffs, Victoria and Berry, South Australia. It links regional electricity markets and uses the ability of HVDC Light® technology to control power flow over the facility. The voltage source converter terminals can act independently of each other to provide ancillary services (such as var support and voltage control) in the weak networks to which it is connected. Operating experience is that its AC voltage control considerably improves voltage stability and power quality in the connected networks. In addition, shunt reactors in neighboring networks can normally be disconnected when the link's AC voltage control is on.

On the loss of an AC line, there is a run-back from 200 MW to zero.

The project has won the Case EARTH Award for Environmental Excellence.

Cable transport for MurrayLink project

Cable laying for MurrayLink project

1.2.7 Troll A, Norway

- Client need
Environmentally-friendly electric power to feed compressors to increase the natural gas production of the platform, combined with little need of manpower for operation.

- ABB response
2 x 40 MW HVDC Light® converters and 272 km (4 x 68 km) ±60 kV HVDC Light® submarine cables. Project commissioned 2005.

- Summary – Troll A
With the Troll A pre-compression project, HVDC transmission converters are, for the first time, being installed offshore on a platform. The transmission design for this first implementation is for 40 MW, ±60 kV, and converters for two identical transmissions have been installed and tested. On the Troll A platform, the HVDC Light® transmission system will directly feed a high-voltage variable-speed synchronous machine designed for compressor drive with variable frequency and variable voltage, from zero to max speed (0-63 Hz) and from zero to max voltage (0-56 kV).

The inverter control software has been adapted to perform motor speed and torque control. The control hardware is identical for rectifier and motor converters.

Over the entire motor operating range, unity power factor and low harmonics are assured, while sufficiently high dynamic response is always maintained. There is no telecommunication for control between the rectifier control on land and the inverter motor control on the platform - the only quantity that can be detected at both ends of the transmission is the DC-link voltage.

However, the control system has been designed so that, together with a telecommunication link, it could provide for land-based operation, faultfinding and maintenance of the platform station.

1.2.8 Estlink HVDC Light® link, Estonia - Finland

- Client need
Improved security of the electricity supply in the Baltic States and Finland.

Reduced dependence of the Baltic power systems and an alternative electricity purchase channel to cover potential deficits in generating capacity.

- ABB response
350 MW HVDC Light® converters and 210 km (2 x 105 km) ± 150 kV HVDC Light®, submarine/land cables. Project commissioned 2006.

- Summary – Estlink
Estlink is a 350 MW, 31 km underground/ 74 km submarine cable transmission between the Harku substation in Estonia and Espoo substation in Finland. It links the Baltic power system to the Nordpool market and uses the ability of HVDC Light® technology to control the power flow over the facility. The voltage source converter terminals can act independently of each other to provide ancillary services (such as var support and voltage control), thereby improving the voltage stability of the Estonian grid. The black-start capability is implemented at the Estonian side i.e. the converter is automatically switched to household operation if the AC grid is lost making a fast energization of the network possible after a blackout in the Estonian network. The implementation phase of the project was 19 months, and the link has been in operation since the end of 2006.

The HVDC Light® station at Harku on the Estonian side of the link.

1.2.9 Valhall Re-development Project

- Client need
Supply of electric power from shore, to replace existing gas turbines offshore and feed the entire existing field, as well as a new platform. The important issues are to minimize emissions of CO_2 and other climate gases and, at the same time, to reduce the operating and maintenance costs of electricity offshore.

- ABB response
HVDC Light® converter stations onshore and offshore rated 78 MW at 150 kV. The project will be commissioned 2009.

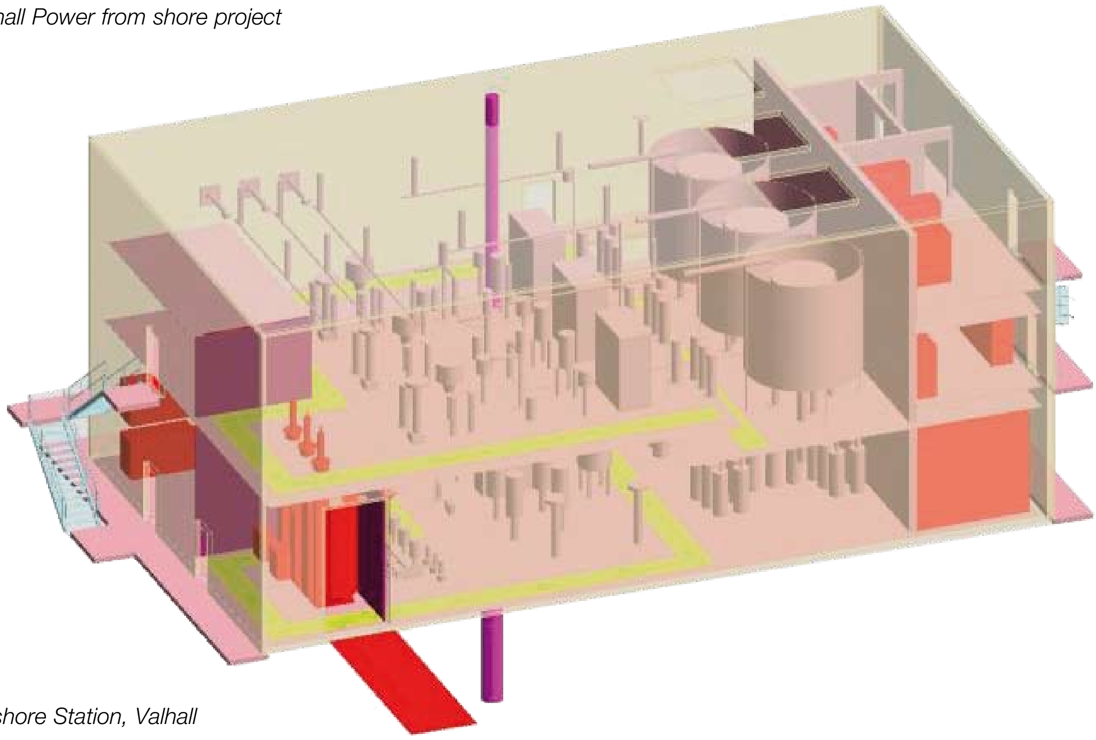
Valhall Power from shore project

- Summary - Valhall Re-development project
As a part of the redevelopment of the Valhall field in the Norwegian sector, ABB will provide the converter stations to enable 78 MW to be supplied over a distance of almost 300 km from shore to run the entire field facilities, including a new production and living quarters platform.

The main factors behind the decision to choose power from shore were:
- reduced costs
- improved operational efficiency
- minimized greenhouse gas emissions
- improvement of all HSE elements

These factors contribute to the customer BP's vision of a safe, intelligent, maintenance-free and remotely controllable field of the future. In addition, the HVDC Light® system will provide a very high quality electric supply with respect to voltage and frequency, including during direct online start-up of the large gas compressor motors, thereby eliminating the need for additional soft start equipment.

The onshore station will be located at Lista on Norway's southern coast. Here the alternating current will be taken from the Norwegian grid at 300 kV and converted to direct current. This will be transmitted at 150 kV over a distance of 292 km via a single power cable with an integrated metallic return conductor to the new Valhall platform. There it will be converted back to AC power at 11 kV in the HVDC module and distributed to all the platforms in the Valhall field.



Offshore Station, Valhall

1.2.10 NordE.ON 1 offshore wind connection - Germany

- Client need

A 200 km long submarine/land cable connection from an offshore wind park to be operational within 24 months.

- ABB response

400 MW HVDC Light® converters, one offshore on a platform and one land-based and 400 km (2 x 200 km) ±150 kV HVDC Light® submarine/land cables. The project will be commissioned 2009.

- Summary - NordE.ON 1 offshore wind connection

The NordE.ON 1 offshore wind farm cluster will be connected to the German grid by a 400 MW HVDC Light® transmission system, comprising 75 km underground and 128 km submarine cable. Full Grid Code compliance ensures a robust network connection.

For both the offshore and the onshore part, most equipment will be installed indoors, thus ensuring safe operation and minimal environmental impact.

Independent control of active and reactive power flow with total control of power from zero to full power without filter switching enables smooth and reliable operation of the offshore wind farm.

A proven extruded cable technology is used that simplifies installation on land and at sea allowing very short time for cable jointing. The oil-free HVDC Light® cables minimize the environmental impact at sea and on land.

In operation, the wind power project will reduce CO_2 emissions by nearly 1.5 million tons per year by replacing fossil-fuel generation.

The transmission system supports wind power development in Germany.

1.2.11 Caprivi Link Interconnector

- Client need

Import of hydro power and coal-fired power from Zambia to ensure a secure power supply in Namibia utilizing an HVDC Light® interconnection of two weak AC networks through a 970 km long ±350 kV overhead line.

In addition:
- Accurate AC voltage control of the weak interconnected AC networks.
- Feed of a passive AC network in the Caprivi strip.

- ABB response

HVDC Light® converter stations designed for a DC voltage of ±350 kV to ground, to be built in two stages:

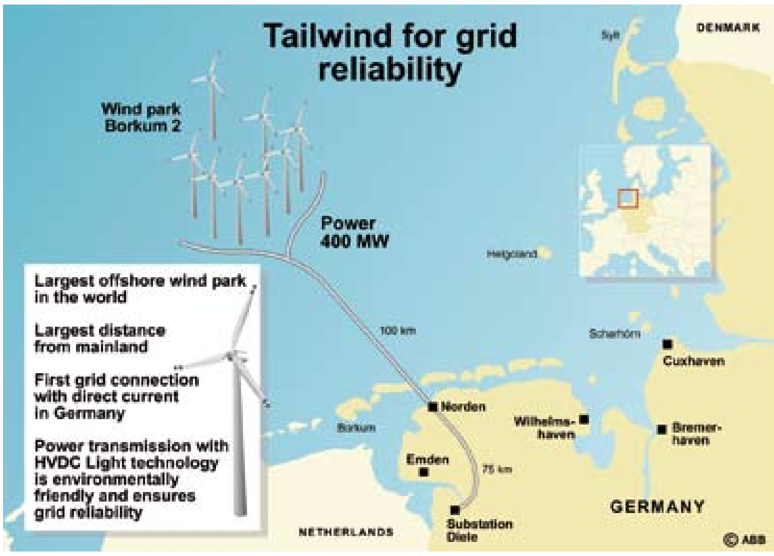
- first stage: a monopole 300 MW (-350 kV to ground)
- second stage: an upgrade to 2 x 300 MW bipole (±350 kV).

The monopole will be put into operation at the end of year 2009. Electrode stations about 25 km from the converter stations.

- Summary – Caprivi Link Interconnector

The Caprivi Link Interconnector will be 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 AC voltages are 320 kV and 400 kV at Zambezi and Gerus respectively.

The converter stations will be interconnected by a 970 km long, bipolar ±350 kV DC overhead line. The conductors of both the negative and positive polarity will be mounted on the same poles. There will be double-circuit electrode lines with a length of about 25 km.



The NordE.ON 1 offshore wind connection

In the monopole stage, the link will be operated with parallel DC lines and earth return to reduce line losses. In the bipole stage, the link will be operated as a balanced bipole with zero ground current.

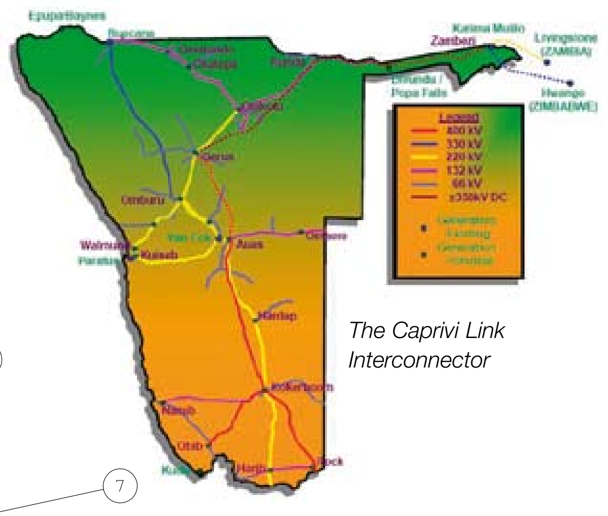
The AC networks of today are extremely weak at both ends, with short-circuit power levels of around 300 MVA and long AC lines which connect to remote generator stations. Due to this fact, the AC networks are also exposed to a risk of 50 Hz resonance. ABB has studied the crucial AC and DC fault cases and verified that the dynamic performance of the HVDC Light® is in line with the requirements of the client.

The condition for the upgrade to a 2 x 300 MW bipole is that the AC networks at Zambezi and Gerus are reinforced, including a new connection to the Hwange coal fired power station in Zimbabwe.

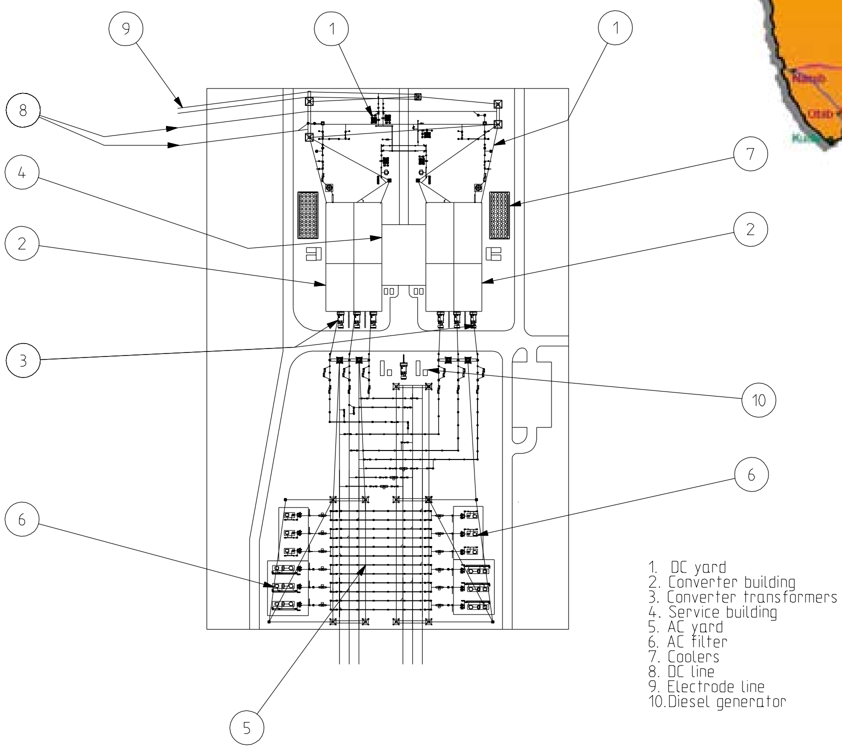
The Zambezi and Gerus converter stations will control the AC voltages in the surrounding grids rapidly and accurately over the entire range of active power capability, by a continuous adjustment of the reactive power absorption and generation between - 130 Mvar and + 130 Mvar.

In the event of outage of the connecting AC lines to Zambezi during power import to Namibia, the power transmission can be reversed rapidly in order to re-energize and feed the black AC network at Zambezi.

The client evaluated possible transmission alternatives and found that the HVDC Light® technology is the most feasible economically and technically solution.



The Caprivi Link Interconnector



Station Layout, Caprivi Link Interconnector

2 Applications

2.1 General

A power system depends on stable and reliable control of active and reactive power to keep its integrity. Losing this control may lead to a system collapse. Voltage source converter (VSC) transmission system technology, such as HVDC Light®, has the advantage of being able almost instantly to change its working point within its capability, and to control active and reactive power independently. This can be used to support the grid with the best mixture of active and reactive power during stressed conditions. In many cases, a mix of active and reactive power is the best solution compared with active or reactive power only. VSC transmission systems can therefore give added support to the grid.

As an example, simulations done at ABB have shown that, for a parallel case (AC line and DC transmission), where the VSC transmission system is connected in parallel with an AC system, the VSC transmission system can damp oscillations 2-3 times better than reactive shunt compensation.

The benefits with a VSC transmission system during a grid restoration can be considerable, since it can control voltage and stabilize frequency when active power is available at the remote end. The frequency control is then not limited in the same way as a conventional power plant where boiler dynamics may limit the operation during grid restoration.

With the above benefits, HVDC Light® is the preferred system to be used for a variety of transmission applications, using submarine cables, land cables and back-to-back.

2.2 Cable transmission systems

2.2.1 Submarine cables

- Power supply to islands

The power supply to small islands is often provided by expensive local generation, e.g. diesel generation. By installing an HVDC Light® transmission system, electricity from the mainland grid can be imported. Another issue is the environmental benefits to the island by reducing emission from local generation.

Since HVDC Light® is based on VSC technology, the converter can operate without any other voltage source on the island, i.e. no local generation on the island is needed for proper operation of the system.

- Remote small-scale generation

Remote small-scale generating facilities are very often located on islands that will not need all the generated power in all situations. This power can then be transmitted by HVDC Light® to a consumer area on the mainland or an adjacent island.

- Interconnecting power systems

The advantages of HVDC Light® are of high value when connecting between individual power systems, especially when they are asynchronous. This refers to the possibilities for controlling the transmitted power to an undertaken value, as well as being able to provide and control reactive power and voltage in both the connected networks.

- Power to/from/between Offshore platforms

With its small footprint and its possibilities to operate at low short-circuit power levels or even to operate with a “black” network, HVDC Light® has made it possible to bring electricity:

- from the shore to the platform
- from platform to shore
- between platforms

The most important and desirable characteristics for offshore platform installations are the low weight and volume of the HVDC Light® converter. Offshore, the converter is located inside a module with a controlled environment, which makes it possible to design the converter even smaller for an offshore installation than for a normal onshore converter station.

2.2.2 Underground cables

- Interconnections

The environmental advantages of HVDC Light® are of high value when connecting two power systems. This refers to the possibilities for controlling the transmitted power to the desired value, as well as improving AC network stability by providing and controlling reactive power and voltage support in the connected networks. Other important factors are: avoiding loop flows, sharing of spinning reserve, emergency power etc.

The rapid AC voltage control by HVDC Light® converters can also be used to operate the connected AC networks close to their maximum permitted AC voltage and in this way to reduce the line losses in the connected AC networks.

- Bottlenecks
In addition to the power transmitted by the HVDC Light® system, an HVDC Light® transmission in parallel with an existing AC line will increase the transmitting capacity of the AC line by the inherent voltage support and power stabilizing capability of the HVDC Light® system.

- Infeed to cities
Adding new transmission capacity via AC lines into city centers is costly and in many cases the permits for new right-of-ways are difficult to obtain. An HVDC Light® cable needs less space than an AC overhead line and can carry more power than an AC cable, and therefore it is often the only practical solution, should the city center need more power. Also, the small footprint of the HVDC Light® converter is of importance for realizing city infeed. Another benefit of HVDC Light® is that it does not increase the short-circuit current in the connected AC networks.

2.3 DC OH lines

HVDC Light® converters can operate in combination with DC overhead lines forming a proper transmission system. An example of this is the Caprivi Link Interconnector in Namibia.

- see 1.2.11

2.4 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.

2.4.1 Asynchronous Connection

If the AC network is divided into different asynchronous areas, connection between the areas can easily be done with HVDC back-to-back converters. This gives a number of advantages:

- Sharing of spinning reserve.
- Emergency power exchange between the networks
- Better utilization of installed generation in both networks
- Voltage support
- etc.

In many cases, the connection between two asynchronous areas is made at a weak connection point in AC systems on the borders of the areas. With its possibilities of operating at low short-circuit ratios, HVDC Light® is very suitable for this type of connection.

2.4.2 Connection of important loads

For sensitive loads, an HVDC Light® back-to-back system is of importance for keeping the AC voltage and AC frequency on proper levels if the quality of those properties of the connected AC network is not sufficient for the connected load. The fast reactive power control properties of HVDC Light® can be used for flicker mitigation.

2.5 HVDC Light® and wind power generation

HVDC Light® is a transmission system which has characteristics suitable for connecting large amounts of wind power to networks, even at weak points in a network, and without having to improve the short-circuit ratio.

This is contrary to conventional AC transmission systems, which normally require a high SCR compared with the power to be entered. With the imminent arrival of wind power farms and accounting for a considerable share of the total power generation in a network, wind power farms will have to be as robust as conventional power plants and stay online during various contingencies in the AC network. Various types of compensation will then be needed to preserve power quality and/or even the stability of the network.

HVDC Light® does not require any additional compensation, as this is inherent in the converters. It will therefore be an excellent tool for bringing wind power into a network

2.6 Comparison of AC, conventional HVDC and HVDC Light®

- Comparison of DC cable system and AC cable system

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

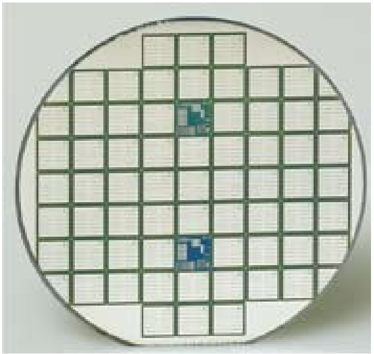
AC cable system
- Cable capacitance limits the practical cable length
- Reactive compensation is needed

Comparison of HVDC Light® and conventional HVDC

- HVDC Light®, power from 50 – 1100 MW

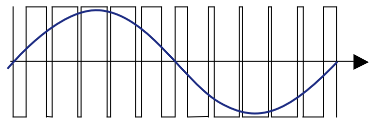
- Each terminal is an HVDC converter plus an SVC
- Suitable both for submarine and land cable connections
- Advanced system features
- Footprint (e.g. 550 MW): 120 x 50 x 11 meters
- Short delivery time

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



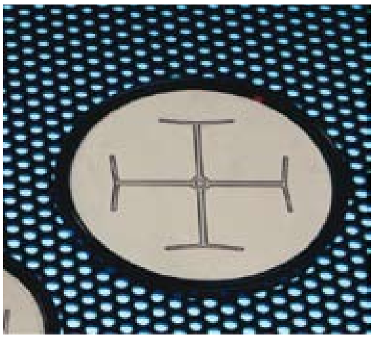
- The IGBT can be switched off with a control signal. Fully controllable.

= forced commutation up to 2000 Hz

- Conventional HVDC, power up to 6400 MW

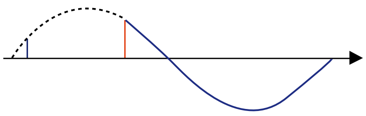
- Most economical way to transmit power over long distances.
- Long submarine cable connections.
- Around three times more power in a right-of-way than overhead AC
- Footprint (e.g. 600 MW): 200 x 120 x 22 meters

Thyristor used as active component in valves



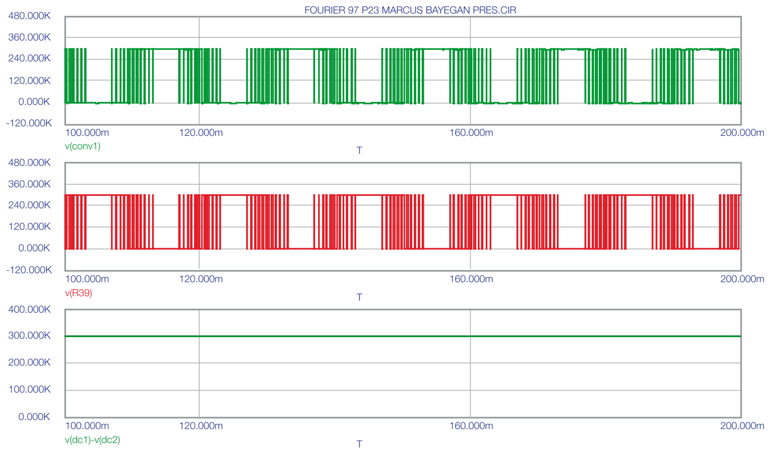
- Single silicon wafer
- Both forward and reverse blocking capability
- Very high surge current capability
- No gate turn-off; line commutated

Phase angle control

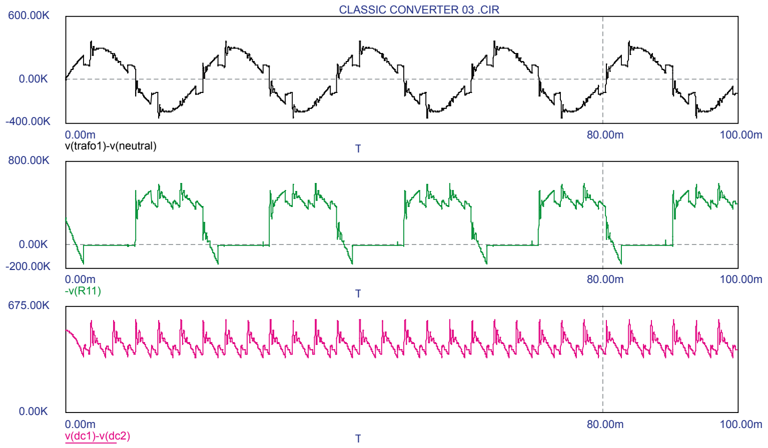


- The thyristor cannot be switched off with a control signal.
- It automatically ceases to conduct when the voltage reverses.

= line commutated, 50/60 Hz



- Upper trace: Reactor voltage
- Middle trace: Valve voltage
- Lower trace: DC Voltage

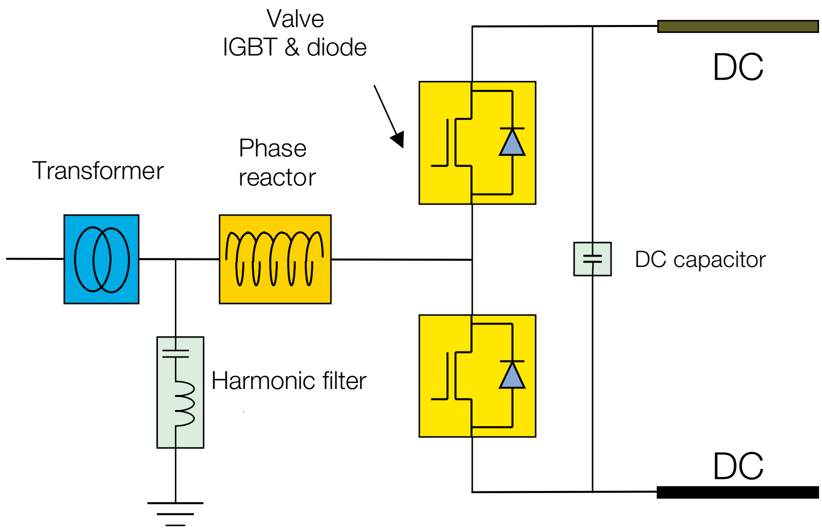


- Upper trace: Transformer voltage
- Middle trace: Valve voltage
- Lower trace: DC voltage

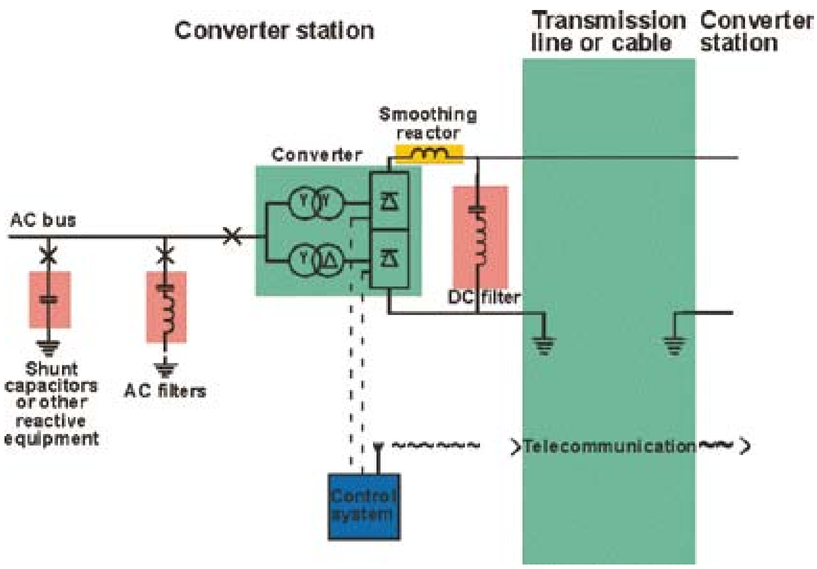
HVDC Light® deep sea cables

Mass impregnated HVDC cable

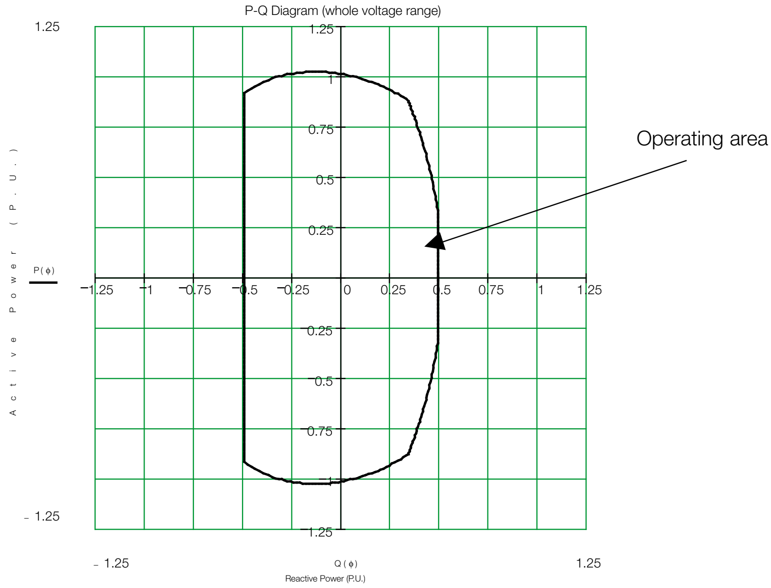
- Simplified single-line diagram for HVDC Light®



- Simplified single-line diagram for conventional HVDC

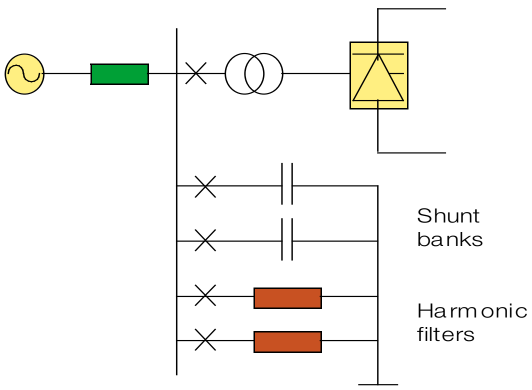


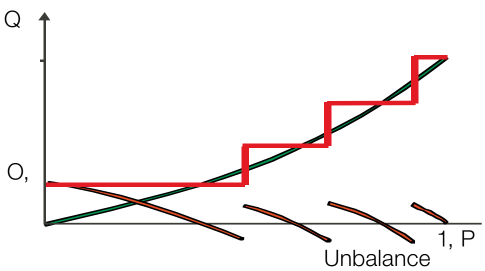
- An HVDC Light® can control both active and reactive power



Y-axis : active power

- Reactive power exchange for conventional HVDC





2.7 Summary of drivers for choosing an HVDC Light® application

2.7.1 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
- Sharing 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 the HVDC Light® Station is not connected to the DC line (staged implementation: build one or two stations for voltage stabilization – connect them later with cables and you have an interconnection).

2.7.2 Undergrounding by cables

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

2.7.3 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 off-shore applications

2.7.4 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

2.7.5 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)

2.8 HVDC Light® cables

2.8.1 Long lifetime with HVDC

The inherent lifetime of insulating materials is better for HVDC than for AC.

2.8.2 Submarine cables

- Low losses
HVDC cables are generally much more efficient for long-distance transmissions than AC cables, in particular for high 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.

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.

The following example shows the difference:

Transmission of 550 MW by submarine cables for a distance of 75 km:

HVDC cable:

150 kV HVDC Light® cables, 2 cables with copper conductor cross-section of 1400 mm2 and steel wire tensile armor. The weight of the two cables is 2 x 32 kg/m = 64 kg/m.

AC cable:

220 kV XLPE cable, 3 cables with copper conductor cross-section of 1600 mm^2 and copper wire tensile armor. The weight of the three cables is 3 x 60 kg/m = 180 kg/m.

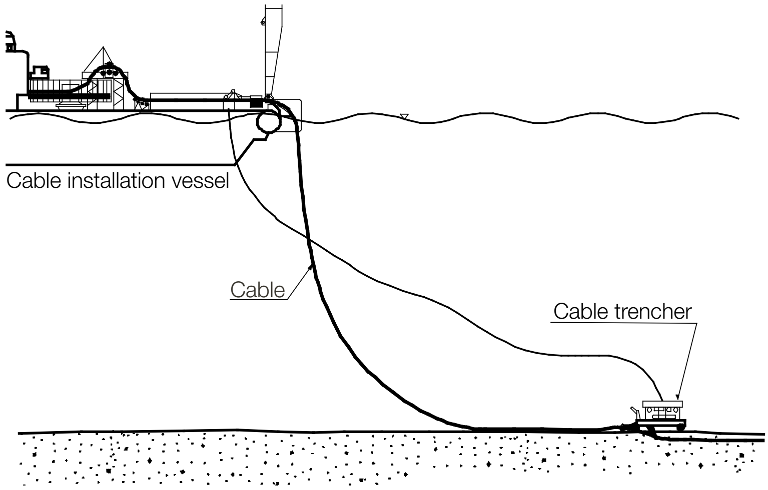
- Deep sea waters
HVDC Light® cables are suitable for large water depths, for the following reasons:

- The polymeric insulation is mechanically robust.
- The HVDC cables are generally less heavy than AC cables for the same transferred power. This gives lower tensile force during laying of the cables.
- It is advantageous to use galvanized steel wires for tensile armor. A 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 thus good.

- The cable can be coiled on a cable laying ship (except for cables with double cross laid armor for large depths). The possibility of coiling the cables makes it possible to lay the cable from small barges and transport the cable by cargo ships without turntables for the cables.
- It is possible in most cases to lay the two cables of the bipole close to each other (e.g. by bundling of 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 laying ships with a smaller pay-off wheel, and also smaller trenching equipment.

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



Typical laying and trenching operation


Coiled cable on small cable laying barge

2.8.3 Underground 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:

- Less visual impact
- Smaller width of the required right of way.

- Handling
HVDC Light® cables have many advantages compared with other cable types, e.g.:

- 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 D_e.

When the cable is installed (no force applied to the cable), the bending radius must exceed 12 x D_e.

D_e is the external diameter of the cable.

- Maximum pulling forces for land cables
When the pulling nose is attached to the conductor, the following tensile forces should not be exceeded:

- 70 N/mm^2 for Cu conductors

- 40 N/mm^2 for Al conductors

- Jointing
HVDC Light® cable joints are usually installed inside a portable jointing house, which is placed in the joint bay. This pre-built 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 mono-polar HVDC cable scheme with a current of 1000 amps gives a magnetic field of 20 micro-Tesla 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 micro-Tesla, which is less than 1% of the natural magnetism.

Jointing container, placed over the cables during jointing at MurrayLink.

3 Features

3.1 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 capacitor increases its voltage with increased charge. In a normal design, the stored energy is equivalent to around 2 ms power transmission on the system. 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, quite simply based on measurement of the DC voltage.

3.2 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.

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/reduced through the generation/consumption of reactive power. This means that HVDC Light® can control the AC voltage independently in each station.

3.3 Low power operation

Unlike conventional HVDC converters, the HVDC Light® converter can operate at very low power, and even at zero power. The active and reactive powers are controlled independently, and at zero active power the full range of reactive power can be utilized.

3.4 Power reversal

The HVDC Light® transmission system can transmit active power in any of the 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 conventional HVDC. 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 the power reversal.

3.5 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.

3.6 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.

3.7 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 (electro-mechanical) 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 on and off load demand or using an HVDC Light® connected to an asynchronous grid are methods that can then be considered. These methods have the advantage that they actually take away or inject energy to damp the oscillations.

HVDC Light® is able to do this in a number of 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 Measurement Units can also be a solution to achieve observability.

3.8 Fast restoration after blackouts

HVDC Light® can aid grid restoration in a very favorable way. Voltage support and frequency support are much needed during such conditions. This was proven in August 2003, when the north-east USA experienced a blackout, by the excellent performance of the Cross Sound Cable Project that interconnects Connecticut and Long Island. A black-start capability can be implemented. It can be beneficial for an HVDC Light® operator to speed up grid restoration because the lack of energy (typically the first 6-24 hours) may initiate considerably higher prices for energy. The black-start facility is implemented on the Estonian side of the Estlink HVDC Light® Project.

3.9 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, a “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.

3.10 Flexibility in design

The HVDC Light® station consists of four parts:

- The DC yard, with DC filtering and switches
- The converter, with the IGBT valves and the converter reactors
- The AC filter yard
- 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.

3.11 Undergrounding

Except for back-to-back, HVDC Light® always employs HV cables for DC power transmission. 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.

3.12 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 radiofrequency range, i.e. radio interference. The background is that HVDC Light® operates with high internal current derivatives and a commutation frequency in the order of 1-2 kHz. Such transients and frequencies 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 performance is verified through measurements.

The HVDC Light® converter installation is connected to the AC power grid/system through AC overhead lines or AC cables. Effective filtering prevents current harmonics from loading into the connected AC lines/cables. This means that they can be considered as normal AC lines/cables installed within the power grid/system.

3.13 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.

3.14 Indoor design

To avoid tall steel supporting structures, to facilitate maintenance and to improve personal safety, the AC filters, converter reactors and DC filters are mounted directly on low foundations/supports and are 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.

3.15 Short time schedule

The converter valves and associated control and cooling systems are factory-assembled in transportable enclosures. 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 is 20 months or less, depending of course on local conditions for converter sites and cable route.

4 Products

4.1 General

4.1.1 Modular concept

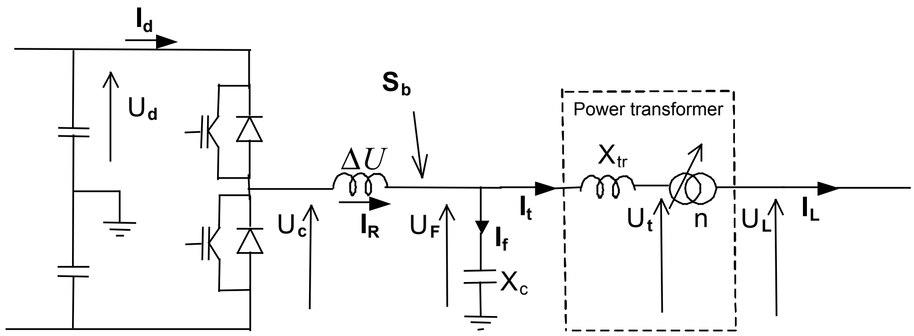
The modular concept of the ABB IGBT valves and standard voltage levels of the DC transmission cables permit different power levels and mechanical setups to be matched optimally to each application.

The modularization of HVDC Light® aims to achieve the most cost-effective technical and topological solution for a specific project, combined with a short delivery time.

The various configurations provide the most economical overall solution. The chosen DC voltages are in line with the ABB High Voltage Cable (HVC) product range, i.e. 80 kV, 150 kV and 320 kV. The chosen valve currents are in line with the ABB Semiconductors product range. The StakPakTM-type IGBTs from ABB Semiconductors are of a modular design, i.e. the active parts, the IGBT and diode chips, are organized in sub-modules. Thus, the current rating of the device is flexible, ranging in steps, i.e. 2 sub, 4 sub and 6 sub. Each sub-module comprises six IGBT chips and three diode chips.

HVDC Light® modules		Currents		
		580A (2 sub)	1140A (4 sub)	1740A (6 sub)
Voltages	± 80 kV	M1	M2	M3
	± 150 kV	M4	M5	M6
	± 320 kV	M7	M8	M9

4.1.2 Typical P/Q diagram



Simplified circuit diagram

The fundamental base apparent power at the filter bus between the converter reactor and the AC filter is defined as follows (see figure above):

$$\overline{S}_b = P + jQ = \sqrt{3} \cdot \overline{U}_F \cdot \overline{I}^*_R$$

The active and reactive power components are defined as:

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

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

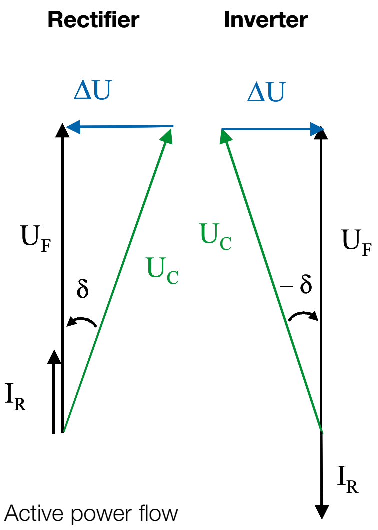
Where:

δ = phase angle between the filter voltage U_F and the converter voltage U_C

L = inductance of the converter reactor

Changing the phase angle controls the active power flow between the converter and the filter bus and consequently between the converter and the AC network.

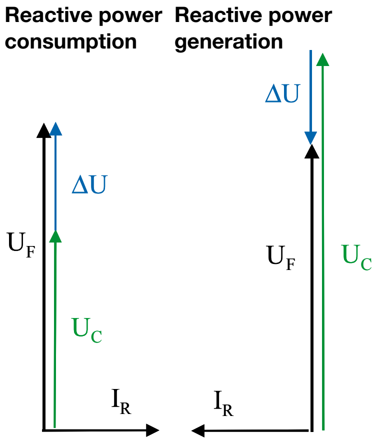
Changing the amplitude difference between the filter voltage UF and the converter voltage UC controls the reactive power flow between the converter and the filter bus and consequently between the converter and the AC network.



Active power flow

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

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



Reactive power flow

If $U_F > U_C$, there is reactive power consumption.

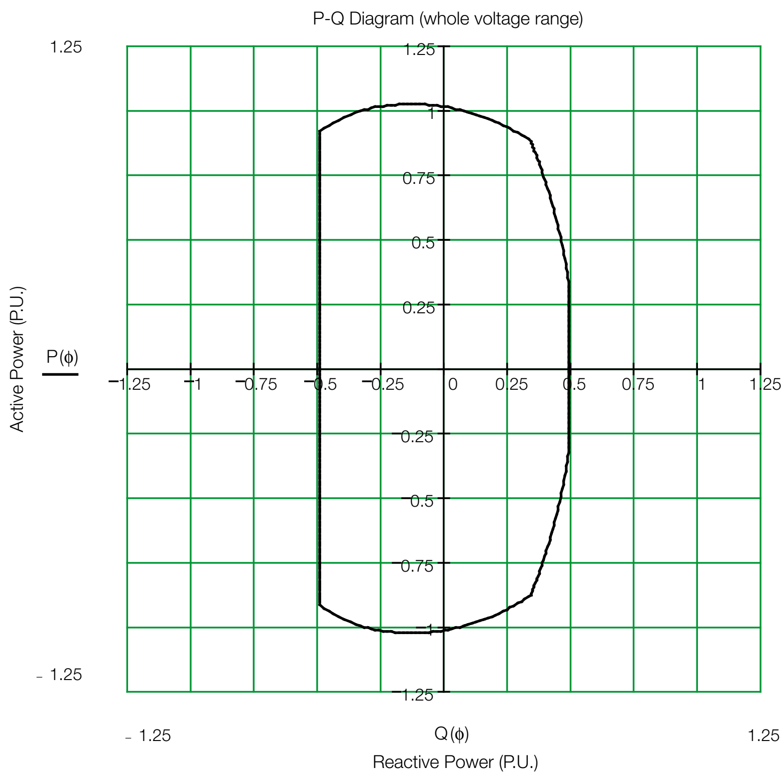
If $U_C > U_F$, there is reactive power generation.

With the OPWM (Optimized-Pulse-Width-Modulation, ref. Section 5.2.3) control strategy, it is possible to create any phase angle or amplitude (up to a certain limit) by changing the PWM pattern. This offers the possibility of controlling both the active and reactive power independently.

The typical P/Q diagram, which is valid within the whole steady-state AC network voltage, is shown in the figure below.

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

Note that there are limitations that have been taken into account in the calculation of this typical P/Q diagram.



Typical P/Q diagram within the whole voltage range. Y-axis: Active power

4.2 HVDC Light® modules

For a specific project, the appropriate HVDC Light® module and cable (if any) have to be selected.

The different HVDC Light® 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 procedure generally used for the selection of a cable size leads to the minimum permissible cross-sectional area, which also minimizes the initial investment cost of the cable.

4.2.1 - 80 kV modules

- Data sheet (power) and power capacity vs. cable lengths

Converter types		**M1**	**M2**	**M3**
Max. DC voltage (pole to ground)	kV	80	80	80
Base power	MVA	101	199	304
DC current (I_{dcN})	A	627	1233	1881

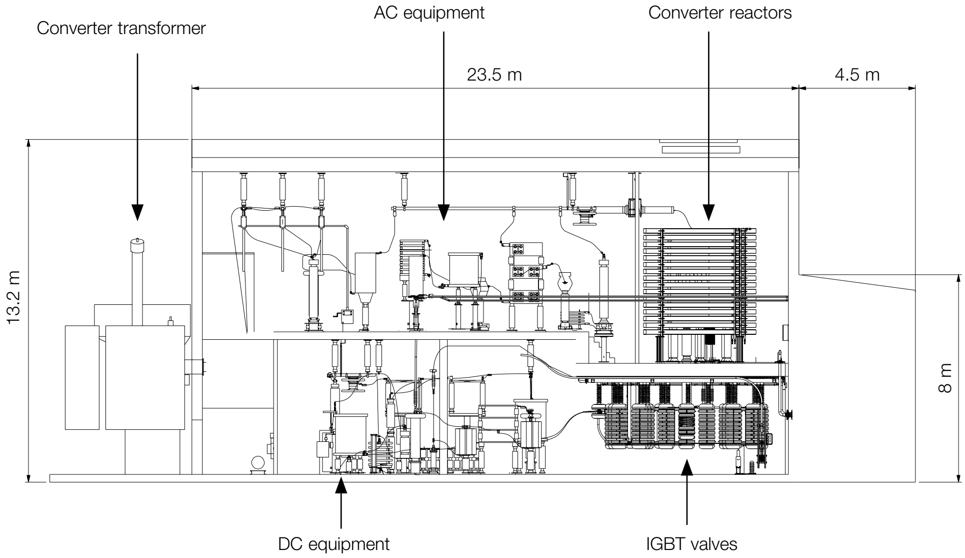
Data for 80 kV modules, typical values

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	102.0	98.7	96.0	93.0			
M2	80	1233	1200	200.5	194.0	191.0	188.5	183.0		
M3	80	1881	2800	306.1	296.0	293.0	290.5	285.0	274.0	

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

- Typical layout

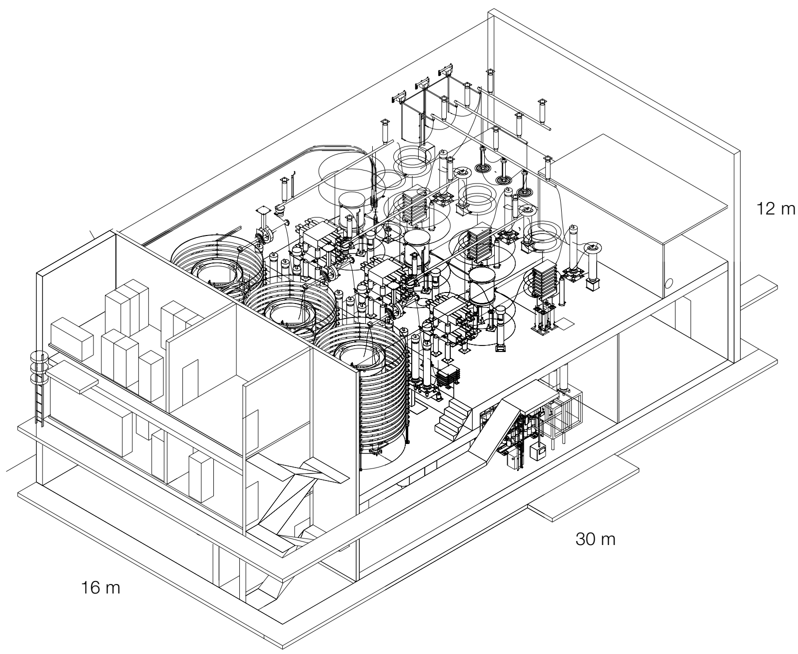
Example of a 78 MW land station



A- Typical layout of an offshore module

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

Example of a 78 MW offshore station



Approximate weight: 1280 tonnes

4.2.2 - 150 kV modules

- Datasheet (power)

Converter types		**M4**	**M5**	**M6**
Max. DC voltage (pole to ground)	kV	150	150	150
Base power	MVA	190	373	570
DC current (I_{dcN})	A	627	1233	1881

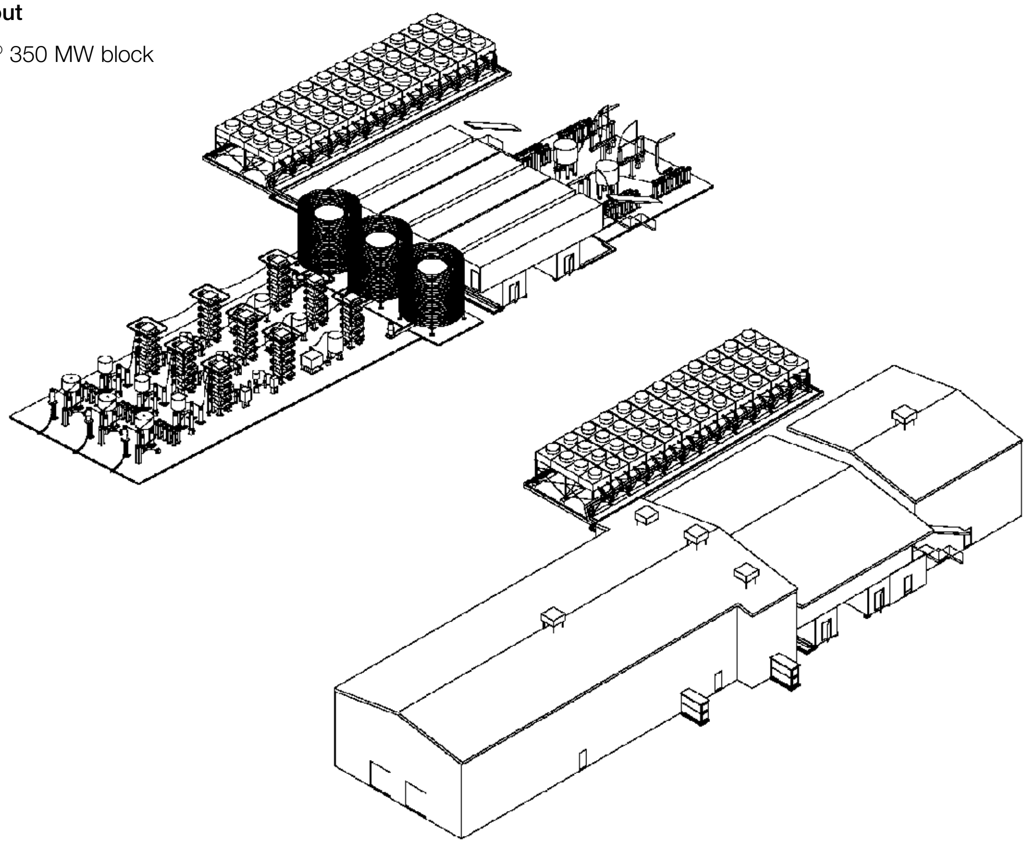
Data for 150 kV modules, typical values

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	191.3	185.0	182.0	179.0	174.0		
M5	150	1233	1200	376.0	363.7	361.0	358.0	353.0	342.0	
M6	150	1881	2800	573.9	555.1	552.0	549.5	544.0	533.0	

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

Typical layout

HVDC Light® 350 MW block



80 x 25 x 11.5 meters

4.2.3 - 320 kV modules

- Datasheet (power)

Converter types		**M7**	**M8**	**M9**
Max. DC voltage (pole to ground)	kV	320	320	320
Base power	MVA	405	796	1216
DC current (I_{dcN})	A	627	1233	1881

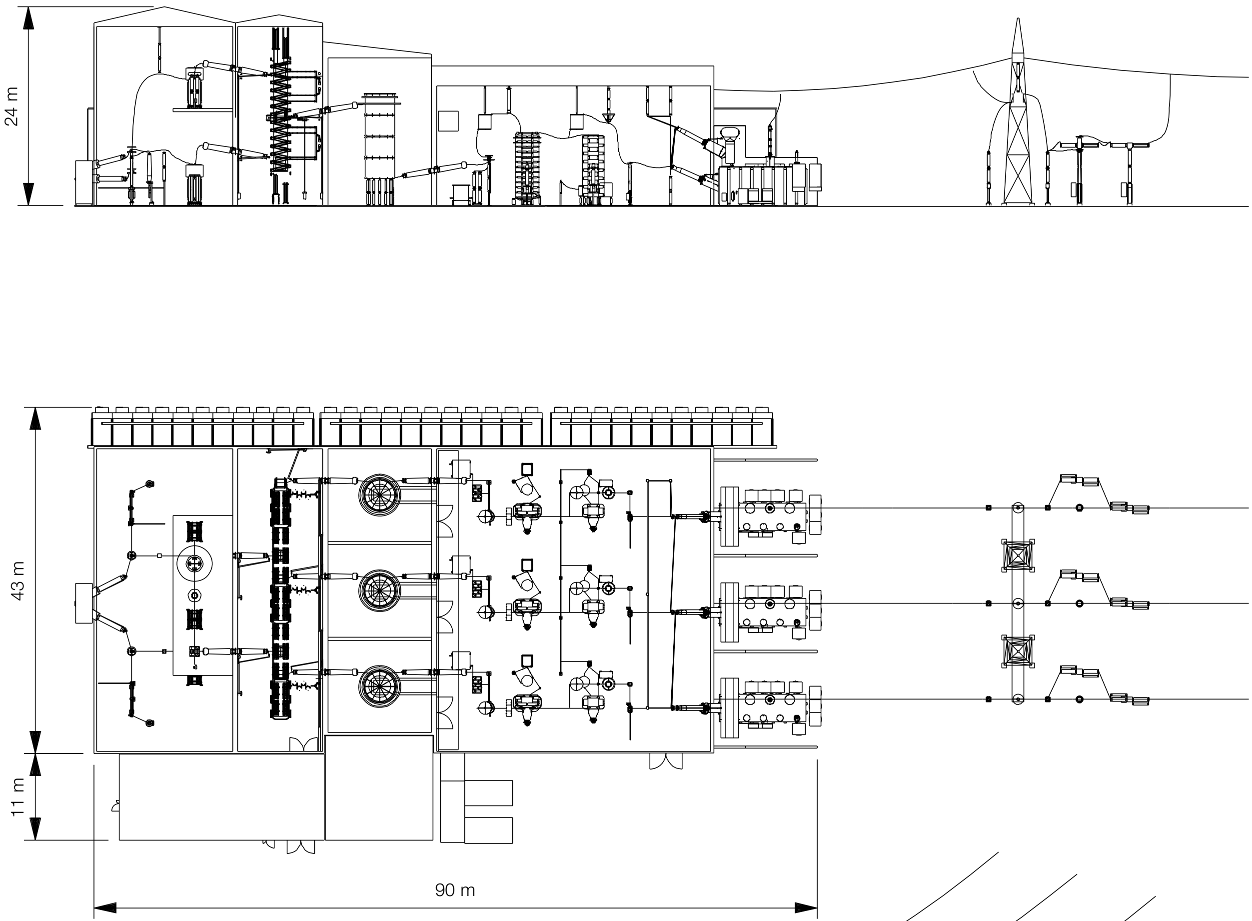
Data for 320 kV modules, typical values

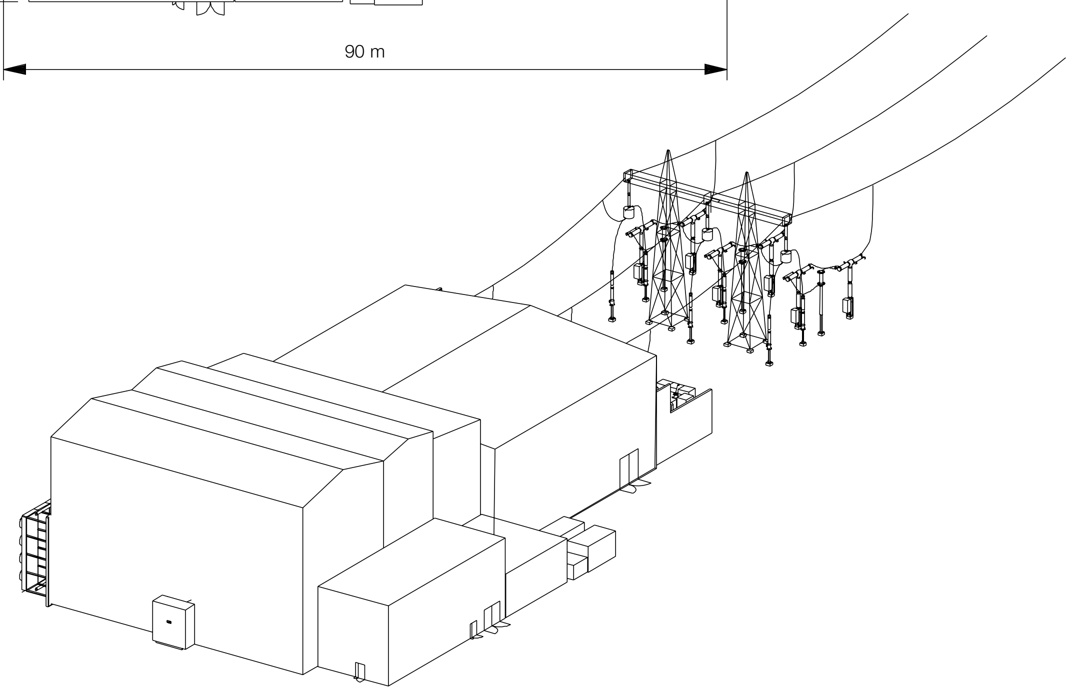
Converter	**DC voltage**	**DC current**	**DC Cable**	**Sending power**	**Receiving power (MW)**					
types	kV	A	Cu in mm²	MW	Back-to-back	50 km	100 km	200 km	400 km	800 km
M7	320	627	300	408.1	396.4	391.4	388.8	382.9	370.6	
M8	320	1233	1200	802.2	775.7	772.8	770.1	764.2	752.5	729.0
M9	320	1881	2800	1224.4	1184.1	1180.8	1178.1	1172.2	1160.5	1137.0

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

- Typical layout

HVDC Light® 1000 MW block



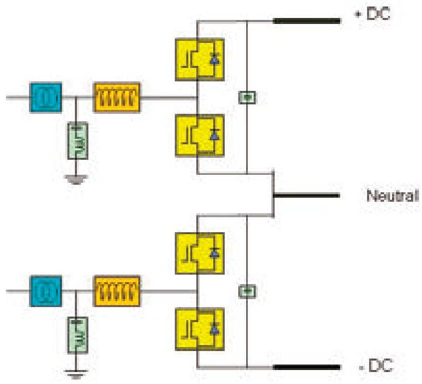


4.2.4 Asymmetric HVDC Light®

As an alternative to balanced (±) DC voltages from the converter, an alternative has been introduced in the valve configuration to make an asymmetric DC voltage possible, i.e. DC voltage from ground to +DC or –DC. A monopolar or bipolar HVDC Light® configuration as used for conventional HVDC can be obtained by this means. Two fully insulated DC cables and one medium voltage cable are needed in the scheme.

The asymmetric HVDC Light® is beneficial for transmission systems with:

- Very high requirements of reliability and/or availability, i.e. only infeed to important loads
- Staged increase of transmitted power for systems with long distances between terminals
- Fulfillment of N-1 criteria. In an HVDC or HVDC Light® system, each individual system or pole is a controllable transmission system, i.e. the remaining system or pole will not be subject to overload if the other system or pole is subject to an outage. Therefore, it is not necessary to reserve capacity margins on a DC system in order to fulfill the N-1 criterion, DC links can rather be operated at their rated power, while still fulfilling the N-1 criterion.
- Applications with OH lines and ground electrodes



Bipolar HVDC Light® scheme

HVDC Light® asymmetric modules		Currents		
		580A (2 sub)	1140A (4 sub)	1740A (6 sub)
Voltages	150kV	M1A	M2A	M3A
	320 kV	M4A	M5A	M6A

Matrix of HVDC Light® asymmetric modules

Converter types		M1A	M2A	M3A
Max. DC voltage (pole to ground)	kV	150	150	150
Base power per pole	MVA	94.6	186.5	285
DC current (I_{dcN})	A	627	1233	1881

Data for asymmetric 150 kV modules, typical values per pole

Converter	DC voltage	DC current	DC cable	Sending power	Receiving power per pole (MW)					
types	kV	A	Cu in mm²	MW	Back-to-back	50 km	100 km	200 km	400 km	800 km
M1A	150	627	300	95.6	92.5	90.0	87.1			
M2A	150	1233	1200	187.9	181,0	179.0	176.7	171.5		
M3A	150	1881	2800	286.9	277.5	274.6	272.3	267.1	256.8	

Transfer capability for different cable lengths, typical values asymmetric 150 kV modules per pole

Converter types		M4A	M5A	M6A
Max. DC voltage (pole to ground)	kV	320	320	320
Base power per pole	MVA	202	397	608
DC current (I_{dcN})	A	627	1233	1881

Data for asymmetric 320 kV modules, typical values per pole

Converter	DC voltage	DC current	DC cable	Sending power	Receiving power per pole (MW)					
types	kV	A	Cu in mm^2	MW	Back-to-back	50 km	100 km	200 km	400 km	800 km
M4A	320	627	300	204.0	197.3	194.1	190.9	185.6		
M5A	320	1233	1200	401.0	387.9	385.0	381.8	376.5	364.8	
M6A	320	1881	2800	612.1	592.1	588.8	586.1	580.2	568.5	

Transfer capability for different cable lengths, typical values for asymmetric 320 kV modules per pole

4.2.5 Selection of modules

The optimization of the entire project, including both converters and cables, must be performed individually for each project, since active/reactive power demand, cable length, sea/land cable 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 from the point of view of cable cost and losses to choose a higher voltage, even if a higher DC voltage increases the cost of the converters. A choice of either a balanced or an asymmetric converter type shall be used based on the distance between terminals, reliability/availability requirements, staged increase of power capacity, etc. This must also be done for each specific project.

4.3 HVDC Light® Cables

4.3.1 Insulation

The 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.

4.3.2 Submarine Cable Data

Cable data (capability, losses, etc., for submarine cables installed in different tropical and moderate climate zones) are set out below.

HVDC Light® Cable bipole data

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 metre, Thermal resistivity 1.2 K × W /m
Cable: Copper conductor, HVDC polymer insulation, Steel wire armour

Bipolar power transmission is	$P = 2 \times U \times I \times 10^{-3}$	MW
Bipolar transmission losses are	$P = 2 \times R \times 10^{-3} \times I^2$	W/m
Voltage drop at 100% load is	$U = R \times I$	V/km

Area	Resistance	Voltage drop		Losses at 50%		Losses at 100%	
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 metre, Thermal resistivity 1.0 K × W /m
Cable: Copper conductor, HVDC polymer insulation, Steel wire armour

Bipolar power transmission is	$P = 2 \times U \times I \times 10^{-3}$	MW
Bipolar transmission losses are	$P = 2 \times R \times 10^{-3} \times I^2$	W/m
Voltage drop at 100% load is	$U = R \times I$	V/km

Area	Resistance	Voltage drop		Losses at 50%		Losses at 100%	
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

4.3.3 Land Cable data

Cable data (capability), losses etc for land cables installed in different tropical and moderate climate zones) are set out below.

HVDC Light® Cable bipole data

Land Cables

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

Area	Ampacity		±80 kV bipole				±150 kV bipole				±320 kV bipole			
Con-duc-tor	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 metre, Thermal resistivity 1.2 K × W /m
Cable: Aluminium conductor, HVDC polymer insulation, Copper wire screen

Bipolar power transmission is	$P = 2 \times U \times I \times 10^{-3}$	MW
Bipolar transmission losses are	$P = 2 \times R \times 10^{-3} \times I^2$	W/m
Voltage drop at 100% load is	$U = R \times I$	V/km

Area	Resistance	Voltage drop	Losses at 50%			Losses at 100%	
Aluminium conductor	per pole 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 aluminium 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 metre, Thermal resistivity 1.0 K × W /m
Cable: Aluminium conductor, HVDC polymer insulation, Copper wire screen

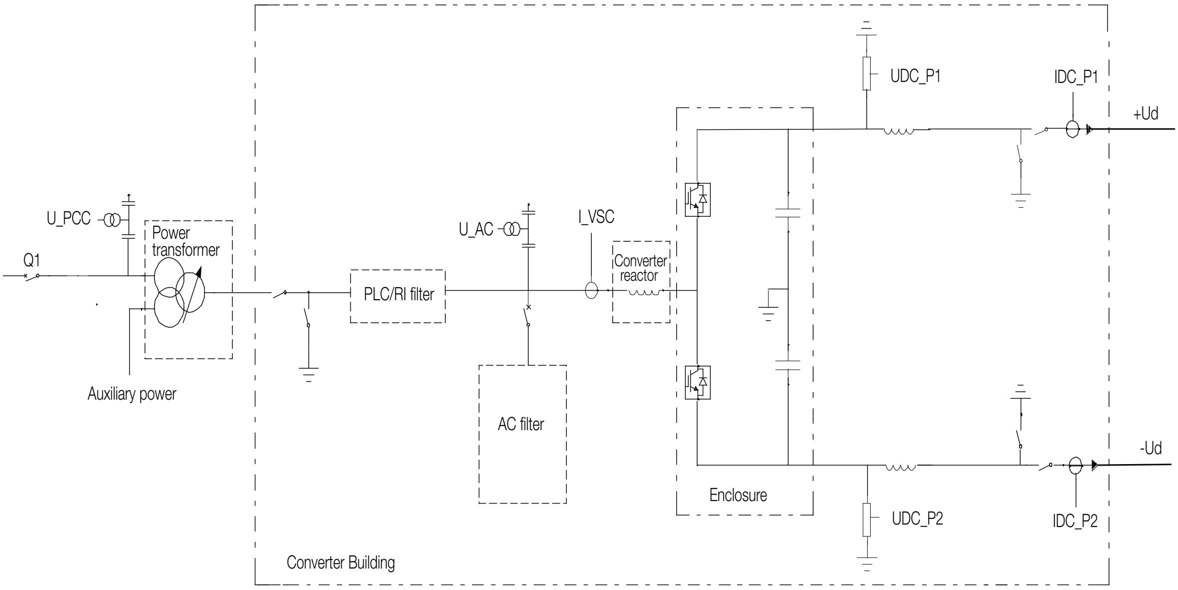
Bipolar power transmission is	$P = 2 \times U \times I \times 10^{-3}$	MW
Bipolar transmission losses are	$P = 2 \times R \times 10^{-3} \times I^2$	W/m
Voltage drop at 100% load is	$U = R \times I$	V/km

Area	Resistance	Voltage drop		Losses at 50%		Losses at 100%	
Aluminium conductor	per pole 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

5 Descriptions

5.1 Main circuit

- Single-line diagram



Single-line diagram of an HVDC Light® Converter

5.1.1 Power transformer

The transformer is an ordinary single-phase or three-phase power transformer, with a tap changer. The secondary voltage, the filter bus voltage, will be controlled with the tap changer to achieve the maximum active and reactive power from the converter, both consumption and generation. The tap changer is located on the secondary side, which has the largest voltage swing, and also in order to ensure that the ratio between the line winding and a possible tertiary winding is fixed.

The current in the transformer windings contains hardly any harmonics and is not exposed to any DC voltage. In order to maximize the active power transfer, the converter generates a low frequency zero-sequence voltage (<0.2 pu), which is blocked by the ungrounded transformer secondary winding.

The transformer may be provided with a tertiary winding to feed the station auxiliary power system.

5.1.2 Converter reactors

The converter reactor is one of the key components in a voltage source converter to permit continuous and independent control of active and reactive power.

The main purposes of the converter reactor are:

- to provide low-pass filtering of the PWM pattern to give the desired fundamental frequency voltage. The converter generates harmonics related to the switching frequency. The harmonic currents are blocked by the converter reactor, and the harmonic content on the AC bus voltage is reduced by an AC filter.

- 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. Refer to Typical P/Q diagram and active and reactive power definitions.

- to limit the short-circuit currents

There is one converter reactor per phase. They consist of vertical coils, standing on insulators. They are several meters tall and several meters in diameter. Shields eliminate the magnetic fields outside the coils.

The short-circuit voltage of the converter reactor is typically 15%.

The stray capacitance across the reactor should be kept as low as possible in order to minimize the harmonics coupled to the filter side of the reactor. The high dv/dt on the bridge terminal at each switching will result in current pulses through all capacitances to ground. These current pulses should be minimized as they pass through the valve. The filter side of the reactor can be considered as ground at high frequencies, and the capacitance across the reactor should therefore be low. These requirements have led to the design of converter reactors with air coils without iron cores.

5.1.3 DC capacitors

The primary objective of the valve DC side capacitor is to provide a low-inductance path for the turned-off current and also to serve as an energy store. The capacitor also reduces the harmonics ripple on the direct voltage. Disturbances in the system (e.g. AC faults) will cause DC voltage variations. The ability to limit these voltage variations depends on the size of the DC side capacitor.

The DC capacitor is an ABB DryQ capacitor. For high voltage applications, this technology makes possible capacitors of a dry, self-healing, metallized film design. The DryQ design has:

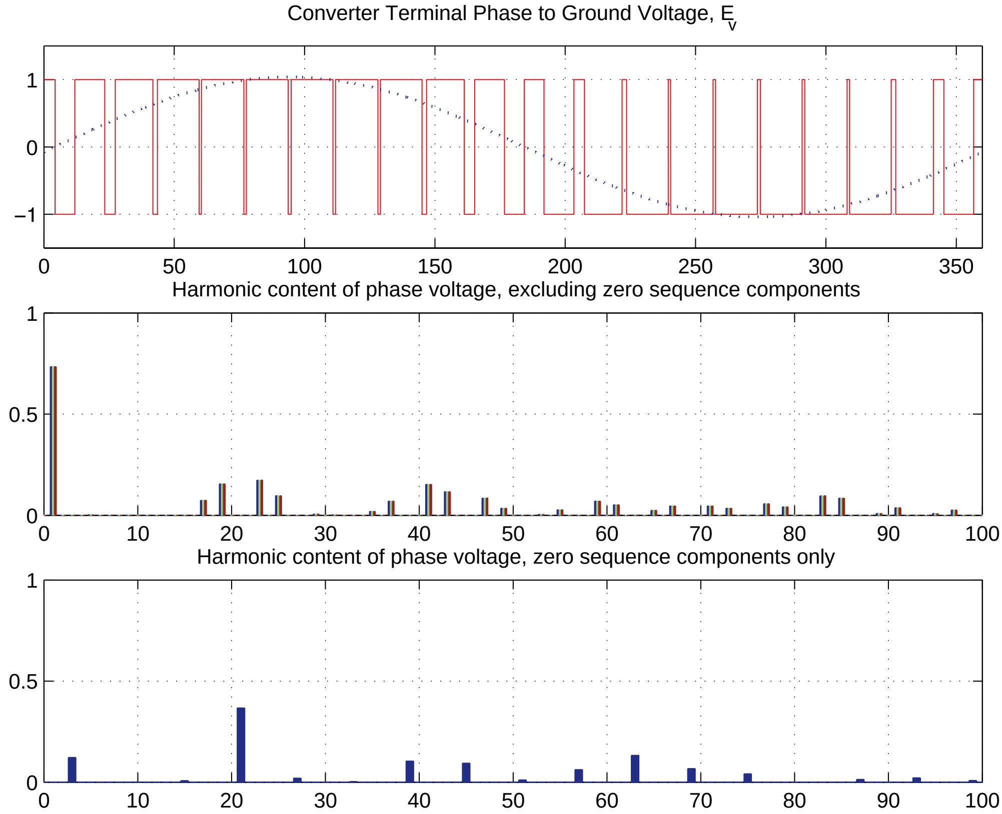
- Twice the capacity in half the volume
- Corrosion-free plastic housing
- Low inductance
- Shortened production time and simplified installation

5.1.4 AC filters

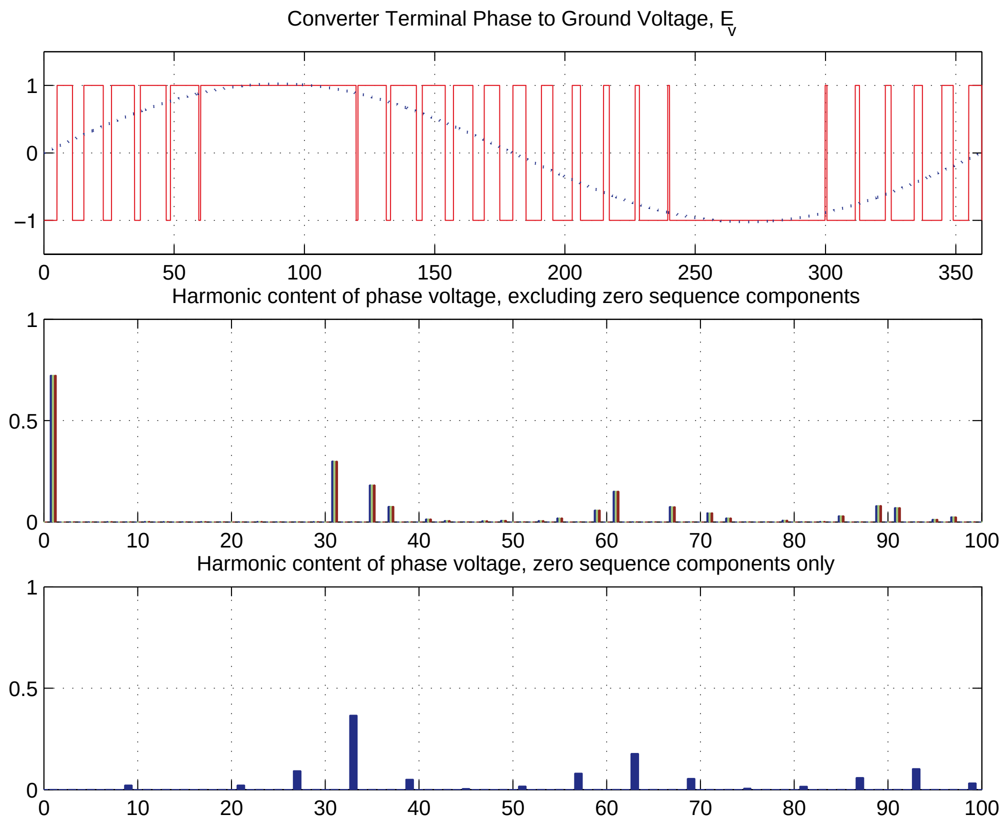
Voltage source converters can be operated with different control schemes, most of which use pulse width modulation to control the ratio between the fundamental frequency voltage on the DC and AC side. Looking at the AC side converter terminal, the voltage to ground will be anything but sinusoidal, as indicated in the figures on the following pages. The most frequent application of voltage source converters is as machine drives (in industrial applications), where this is of less or no concern. However, connecting a voltage source converter to a transmission or distribution system requires the voltage to be made sinusoidal. This is achieved by means of the converter reactor and AC filters.

The distorted waveform of the converter terminal voltage can be described as a series of harmonic voltages $E = \sum_{h=1} E_h \cos(h\Omega_1 t + \alpha_h)$ where E_h is the h:th harmonic EMF. The magnitude of the harmonic EMFs will, naturally, vary with the DC voltage, the switching frequency (or pulse number) of the converter, etc. But it will also depend on the chosen PWM technology of the converter. To illustrate this, the figures below contain two examples:

- A converter utilizing a sinusoidal PWM with 3rd harmonic injection (that is when a 3rd harmonic is added on the fundamental frequency modulator to increase the power rating of the converter).
- A converter using a harmonic cancellation PWM or OPWM.



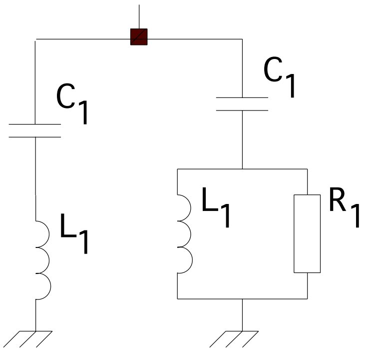
Voltage source converter operated with a sinusoidal PWM with 3rd harmonic injection. The blue dotted line shows the fundamental frequency voltage component of the converter terminal to ground voltage.



Both the above figures give the converter terminal phase-to-ground voltage (with the fundamental component indicated) together with the corresponding harmonic spectrum. The spectrum is given as positive and negative sequence components and zero-sequence components. The power transformer between the filter bus and the connecting AC bus will effectively prevent the latter entering the AC network.

In a typical HVDC Light® scheme, AC filters contain two or three grounded or ungrounded tuned filter branches.

Voltage source converter operated with a harmonic cancellation PWM. The blue dotted line shows the fundamental frequency voltage component of the converter terminal to ground voltage.



Example of an HVDC Light® AC filter.

Depending on filter performance requirements, i.e. permissible voltage distortion, etc., the filter configuration may vary between schemes. But a typical filter size is somewhere between 10 to 30% of the rated power. Typical requirements on filter performance are

Individual harmonic distortion,

$$D_h = \frac{U_h}{U_1} \approx 1\%$$

Total harmonic distortion,

$$THD = \sqrt{\sum_h D_h^{\,2}} \approx 1.5\% \text{ to } 2.5\%$$

Telephone influence factor,

$$TIF = \sqrt{\sum_h \left(5hf_1 C_{message(hf_1)} D_h\right)^2} \approx 40 \text{ to } 50$$

The above indices are all based on the voltage measured at the point of connection of the DC scheme. The first two are direct measures of voltage quality, whilst the third, TIF, is a weighted measure and is a commonly used indication of expected telephone interference. The TIF value is based on the Cmessage weight presented in E.E.I. Publication 60-68.

C-message weight

5.1.5 DC filters

For HVDC Light® converters used in combination with HVDC Light® cables, the filtering on the DC side by the converter DC capacitor and the line smoothing reactor on the DC side are considered to provide sufficient suppression of any harmonics.

However, under certain circumstances, if the DC cable route shares the same right of way or runs close by subscribers telephone wires, railroad signaling wires or similar, there is a possibility of exposure to harmonic interference from the cable. Under these circumstances and for conditions where a local preventive measure is not feasible, e.g. improving the shielding of subscriber wires, the third party (telephone company, railway company, etc.) should be consulted for permissible interference limits.

A typical requirement can be expressed as an equivalent weighted residual current fed into the cable pair at each station. The current is calculated as

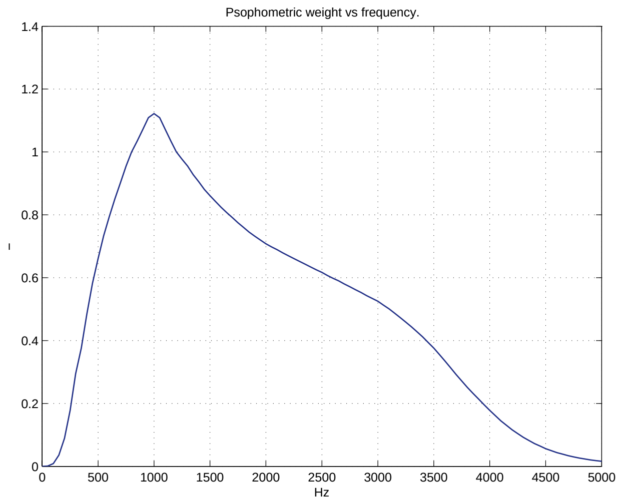
$$I_{eq} = (1/P_{800}) * \sqrt{\sum_h (P_{hf_1} * I_h)^2}$$ where:

- I_{eq} is the psophometrically weighted, 800 Hz equivalent disturbing current.
- I_h is the vector sum of harmonic currents in cable pair conductors and screens at harmonic h
- P_{hf1} is the psophometric weight at the frequency of h times the fundamental frequency.

The weighting factor in this example is the UIT (CCITT) psophometric weighting factor.

Sometimes the C-message factor mentioned above is used instead.

If additional filtering is required, the remedy is to add a filter on the DC side, consisting of either a common mode (zero-sequence) reactor or/ and a single-tuned filter or filters.



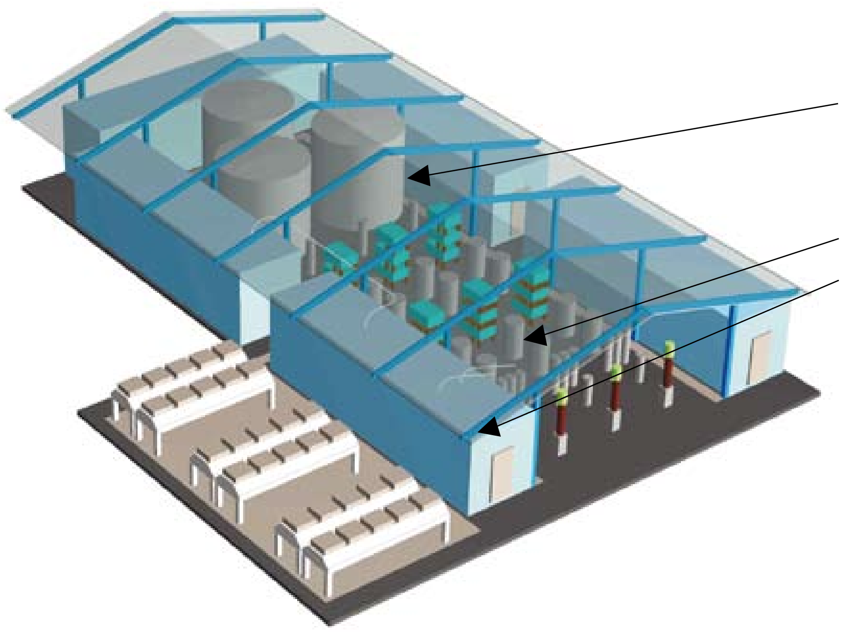
Psophometric weight

5.1.6 High-frequency (HF) filters

In voltage source converters, the necessarily high dv/dt in the switching of valves means that the high frequency (HF) noise generation is significantly higher than for conventional HVDC converters. To prevent this HF noise 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. For example, the valves contain HF damping circuits on both the AC and DC sides to ensure that as little HF disturbance as possible will spread from the valve area.

To further limit HF interference, a radio interference (RI) filter capacitor is connected between the AC bus and earth, and an AC line filter reactor is installed. With these measures, the scheme will meet the requirements of applicable standards for emissions.

If a power line carrier (PLC) is used nearby in the connected power grid, additional PLC filters may be required, i.e. an additional AC line filter reactor and a properly tuned capacitor to earth.



RI defense lines

- Valve and reactor enclosures
- Enclosure cable connections
  - EMC ROX
  - Ferrites
- RI - Filtering
- House
- Earthing system
- EMC approved aux. systems

Applicable standards

- CISPR 11
- ENV50121-5

5.1.7 Valves

- The IGBT position

The semiconductor used in HVDC Light® is the StakPak™ IGBT from ABB Semiconductors. The IGBT (insulated gate bipolar transistor) is a hybrid of the best of two worlds. As a conducting device, the bipolar transistor with its low forward voltage drop is used for handling high currents. 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 three 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 voltage divider 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 voltage divider 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 StakPak™ IGBT with four and six sub-modules.

- Valve function
To be able to switch voltages higher than the rated voltage of one IGBT, several positions are connected in series in each valve. The most important factor is that all IGBTs must turn on and off at exactly the same moment, in order to achieve an evenly distributed voltage across the valve. ABB has a well-proven solution that regulates each IGBT position individually in the valve to the correct voltage level. The flexibility of the IGBT as a semiconducting device also makes it possible to block the current immediately if a short circuit is detected, and thus to prevent damage to the converter. A single valve for a 150 kV module consists of around 300 series-connected IGBTs.

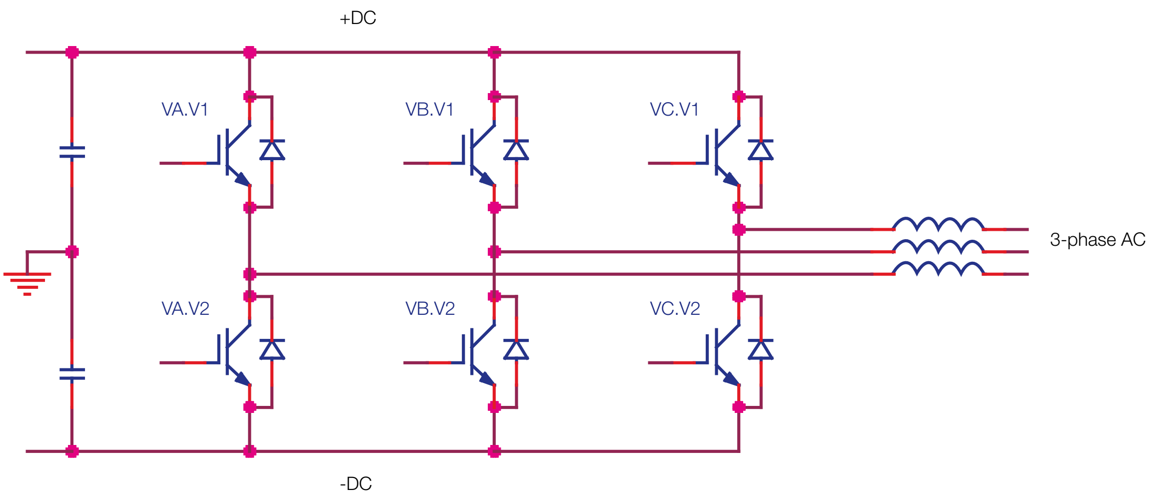
- Valve bridge
HVDC Light® is based on a two-level topology, meaning that the output voltage is switched between two voltage levels. Each phase has two valves, one between the positive potential and the phase terminal and one between the phase terminal and the negative potential. Thus, a three-phase converter has six valves, three phase reactors and a set of DC capacitors. The diagram below shows the schematics of an HVDC Light® converter in principle.

- Mechanical design
The HVDC Light® converter valves are for DC voltages up to 150 kV assembled inside an enclosure made of steel and aluminum. The shielded enclosure helps to improve the electromagnetic compatibility of the converter. Another advantage is that the enclosure is made as a standard container, which simplifies the transport of the converter to the site. With this method, most of the HVDC Light® converter parts can be pre-assembled at the production location to minimize the assembly work on site. Some of the testing can also be done before transportation, thereby reducing the installation and commissioning time on site.

All IGBTs and coolers in a stack are mounted tightly together under very high pressure, in order to minimize contact resistance and to increase cooling capacity.

The stacks are pressed together with glass fiber bolts, which fulfill both insulation and mechanical strength criteria. Circular aluminum shields are mounted around the IGBT stacks to smooth the electrical field around the high-voltage equipment. The stacks are suspended on an insulator from the ceiling of the valve enclosure. This installation method makes the converter resistant to earthquakes and other movements.

Overall, the assembling method with shielded stacks hanging in enclosures with controlled humidity levels makes it possible to reduce the distances between the high-voltage parts and the surroundings. This makes HVDC Light® a compact power transmission technology.



Principle schematic of a three-phase two-level HVDC Light® converter.

Inside a Valve Enclosure

Today, there are no issued standards that fully cover the testing of an HVDC Light® converter valve.

The AC and DC voltage applications are tested according to IEC 60700-1 and IEC 61954, to the extent that the standard is applicable. The switching and lightning impulse tests are performed according to IEC 60060. However, standard IEC 62501 for testing of VSC Valves is under preparation, and as soon as it is valid testing of the HVDC Light® valves will be based on that standard.

All IGBT positions are tested before the stacks are assembled, in a sophisticated routine test line.

In this process, the IGBT, the voltage divider and the gate unit are tested together.

Afterwards, parts of the converter valves are type tested in an H-bridge test setup. The tests are performed on a downscale of the converter valves, with only a few positions in series and with a reduced AC voltage. Four valves are connected in an H-bridge configuration, which makes it possible to test both rectifier and inverter operation. Phase angles, voltages, current and filters can be adjusted to simulate most of the HVDC Light® operation modes.

5.1.8 Valve cooling system

All HVDC Light® positions are equipped with water-cooled heat sinks providing high-efficiency cooling. The valve cooling systems are manufactured by SwedeWater, a member of the ABB group.

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 MACH-2-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.

Valve cooling system.

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.

5.1.9 Station service power

The station service power system is vital for reliable operation of the HVDC Light® station. The design of station service power is focused 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 a yoke winding on the converter transformer.

In this way, the power supply is guaranteed at all times when the station is in operation. The output voltage is 6 –10 kV, which means an intermediate transformer is necessary to provide a 400 V system.

The external power supply is taken from a local AC system provided by the customer and is used as a backup source.

- Duplication of all critical parts, valve cooling pumps, station batteries and battery chargers.

- Automatic changeover
The incomers to the 400 V switchgear have automatic changeover control. The supply coming from the internal AC bus is pre-selected as a primary supply, and the supply from the external local AC system is preselected as a backup supply. If the pre-selected supply fails, changeover to the backup supply takes place within a pre-set time. When the pre-selected supply returns, the changeover system changes back to the primary supply within the preset time.

- Duplication of all critical equipment
- valve cooling pumps

The duplicated valve cooling pumps are controlled by frequency converters for maximum flexibility for the flow control of cooling water. The frequency converter also makes it possible to use a DC backup source to keep the pump running if auxiliary power is lost for a long time.

- station battery system

The control equipment and other station DC loads are supplied from a duplicated station 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.

5.1.10 Fire protection

For HVDC Light® projects, the fire protection area is generally smaller than for conventional HVDC, but the requirements are the same. The design of fire-fighting and fire protection is in accordance with NFPA (National Fire Protection Association) and with the requirements of all authorities having jurisdiction over any parts of the works.

The valve enclosures, the control enclosure and all areas that have a high demand because of sensitive equipment are detected with air sampling systems. The air sampling system can detect smoke at a very early stage. Being able to detect smoke at an early stage is an advantage, since this can prevent unnecessary tripping or shutdown of the station.

The power transformer is isolated by firewalls. Depending on the local regulations or client requirements, the transformer may or may not be protected by a sprinkler system. The converter reactors have smoke detectors.

If necessary, the valve enclosures and other detected areas with air sampling systems can be protected with total flooding by gas or water mist extinguishing systems in accordance with NFPA 2001 or NFPA 750.

If a water pumping system is required, it consists of one electric pump and one standby diesel-driven pump. A ring main water loop will then be located on the site (underground) for a fire-fighting water supply. It is connected to an isolation valve that will bring redundancy in the ring main loop for fire fighting 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 fire fighting water loop.

The signals from the detection system and the pumps will be connected to a fire alarm panel in the operator control room.

5.1.11 Civil engineering work, building and installation

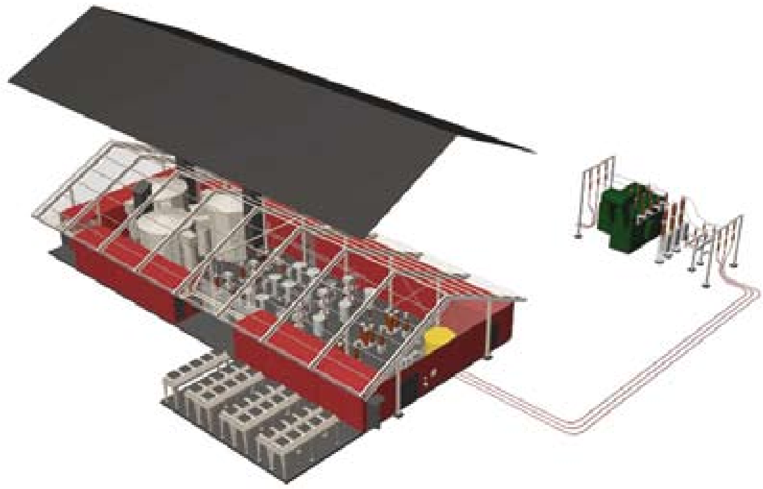
- General
For HVDC Light® systems up to 150 kV, land-based stations are built without a dedicated valve hall. The converter station has a compact layout, with the majority of equipment housed in a typical warehouse-style building. The buildings are made of sheet steel and are provided with doors, stairs and catwalks.

The IGBT's valves are installed in steel enclosures, which are placed on a concrete slab. The control and cooling equipment is normally also installed in enclosures. Concrete slabs are also used for locating the AC filters and DC equipment. A simple steel building is erected over all the equipment. The main functions of the building are HF shielding, noise reduction and weather protection. All the enclosures (valves, control and cooling) have a controlled indoor environment as regards temperature, humidity and cleanness.

The wall cladding of the building is normally metal sheeting, which can be insulated with sound barriers to achieve the required noise level. The building can be fitted with a ventilation system if required.

Transformers and cooling fans are located outside the building. The power transformers are placed on solid foundations. The transformer is connected to the indoor AC filter by cables. If required, conventional AC switchgear with breakers, etc., can be added to connect the power transformer to the AC network.

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.



- Site inspection and testing
System testing is normally the last test activity prior to handing over the HVDC system to the client for operation. Prior to system testing, several other test activities will have been performed.

The general philosophy is that all tests must be performed as early as possible in order to allow early remedial work to be done. The on-site inspection and test activities comprise:

Verifications and tests during civil engineering work and during installation of individual equipment/unit.

- 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, including building 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 specification and contract agreement.

All verifications and tests on site are listed in the inspection and test plan for field tests (ITP).

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.

5.1.12 Availability

When designing a modern HVDC Light® transmission system, one of the main design objectives is to minimize the number of forced outages and the down time due to forced outages and scheduled maintenance.

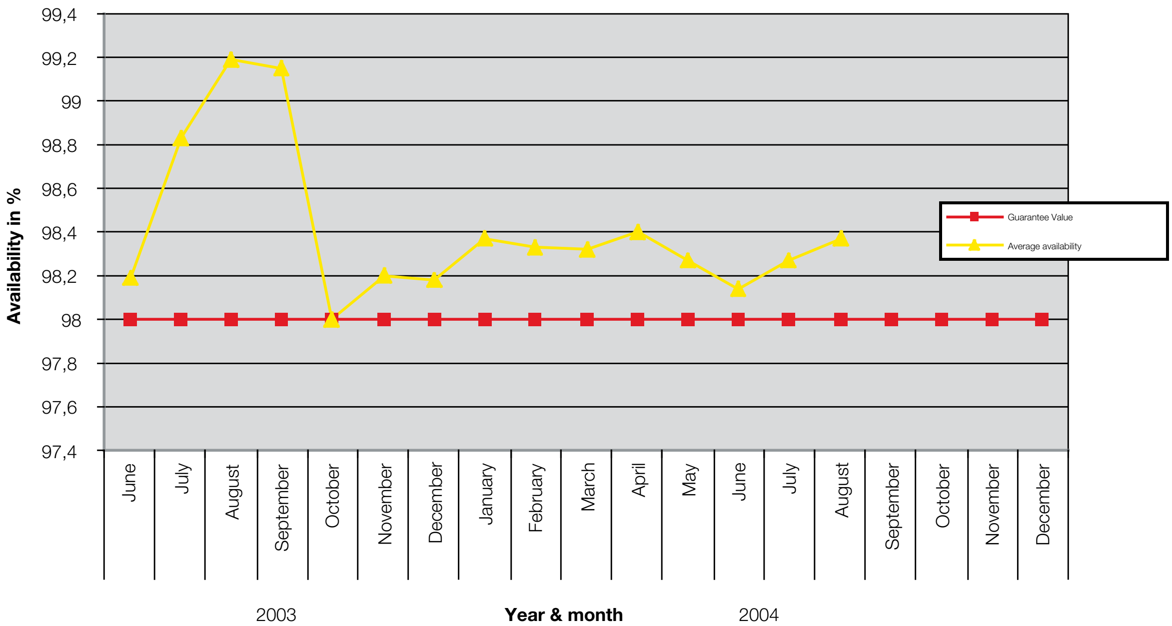
The HVDC Light® transmission is designed according to the following principles in order to assure high reliability and availability:

- simple station design
- use of components with proven high reliability
- automatic supervision
- use of redundant and/or back-up control systems and equipment such as measurements, pumps, etc.
- 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
- the scheduled maintenance time has been kept low thanks to few mechanical parts

Maintainability is increased by the introduction of redundancy up to an economically reasonable level. The maintenance times, especially for work that requires curtailment of the HVDC Light® transmission, should be minimized by the use of exchange modules or components instead of repair.

Observed energy availability from two of our projects in commercial operation is above 98%, as shown in the figure below. Since the number of installed items of equipment is less for an HVDC Light® scheme compared with a conventional HVDC scheme, the target value for availability is equal or even better for HVDC Light® compared with conventional HVDC.

Availability, Cross Sound and Murray Link



1) October 2003, Average availability is decreased by annual preventive maintenance in MurrayLink

5.1.13 Maintainability

The unavailability due to scheduled maintenance depends both on the design of the HVDC Light® transmission and on the organization of the maintenance work. The modern design, which incorporates extensive redundancies for essential systems such as cooling systems, duplicated control systems and station service power, allows most of the maintenance work to be done with no interruption of operation. This work will require 200-400 man-hours per year, depending on the size of the transmission system. As an example, the remaining maintenance effort for a 350 MW module that requires curtailment of the HVDC transmission is estimated to require approximately 160 man-hours per station every second year. The time to do this work is estimated to be 60 hours, the necessary workforce will then be six persons, and the minimum scheduled unavailability will then be a maximum of 0.35% on average per year. However, with increased staff and proper planning, the maintenance work can be performed in a shorter time.

5.1.14 Quality Assurance/ Standards

ABB has developed an effective and efficient quality assurance program complying with ISO 9001 and other applicable standards and an environment management system complying with ISO 14000. The know-how acquired by long experience with HVDC projects of different kinds, solid technical resources and closely developed relations with key sub-suppliers, ensures reliable products in compliance with specifications.

The quality assurance program provides the tool to ensure that 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 (type testing and routine testing for equipment, factory system testing for control equipment), installation, commissioning and commercial operation. The included equipment is in line with applicable IEC standards.

5.1.15 Acoustic noise

A major part of the equipment that generates noise is located inside the buildings, and this noise can be successfully attenuated by appropriately designed acoustic properties of the walls and roof. The station layout should also be adapted to fit acoustical requirements.

There may be several different sound requirements for an HVDC Light® station.

Identifying which of them are valid and may be critical for the design of the plant is a major task at the beginning of the acoustic design process.

The sound requirements usually apply to the areas outside the station, the space inside the station, and the inside of the buildings/enclosures.

Sound requirements for the outside area may vary depending on state regulations, or on local regulations or industry practices.

- Decibel scale

Sound is measured as the sound pressure level (usually referred to as the sound level) and is stated as a decibel (dB) value, which represents a value related to a certain reference sound pressure level.

It is normal that the value used is corrected for the spectral sensitivity of the human ear; this is known as dB(A).

- Sound requirements

The most common sound requirements for the areas outside the station area are set at the following locations.

- At the station fence.
(typically 60 dB)

- At the property line.

- At a given distance /radius from the station;

- At the nearest residences.
(typically 40 dB)

- Acoustic design

To ensure that noise requirements for the plant will be met, it is necessary to design and construct the station correctly from the very beginning.

The process of acoustic design of the plant includes the following steps:

- Identify the noise requirements for the plant
- Identify the real constraints for the noise design
- Influence the layout design so that the noise requirements will be fulfilled
- Predict the expected noise level around the equipment used and the entire plant
- Decide the maximum permissible noise levels for the most significant pieces of equipment
- Decide the acoustic properties of the enclosures, buildings and expected attenuation screens
- Work out the verification procedures for final compliance with the noise requirements for the plant

- Noise sources in an HVDC Light® station

Typical noise sources in the HVDC Light® station are:

- Power transformers;
- Cooling fans for cooling systems;
- Ventilation openings and facades of the equipment buildings;
- PLC filter components;
- Air-conditioning equipment.

- Prediction model

The calculation for prediction of the sound contribution from the HVDC Light® equipment is usually done in a three-dimensional (3-D) model of the plant and its surroundings. The 3-D model is created in the qualified software, which is also used for calculations.

All significant sound sources in the plant are included in such a model. The most essential elements of station surroundings which may influence the sound propagation from the station are also included in the model. 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 the tables containing the exact sound level values for the chosen locations of interest.

5.2 HVDC Light® control and protection

5.2.1 Redundancy design and changeover philosophy

- Active/standby systems

The redundant PCP systems are designed as duplicated systems acting as active or hot standby. At any time only one of the two control systems is active, controlling the converter and associated equipment.

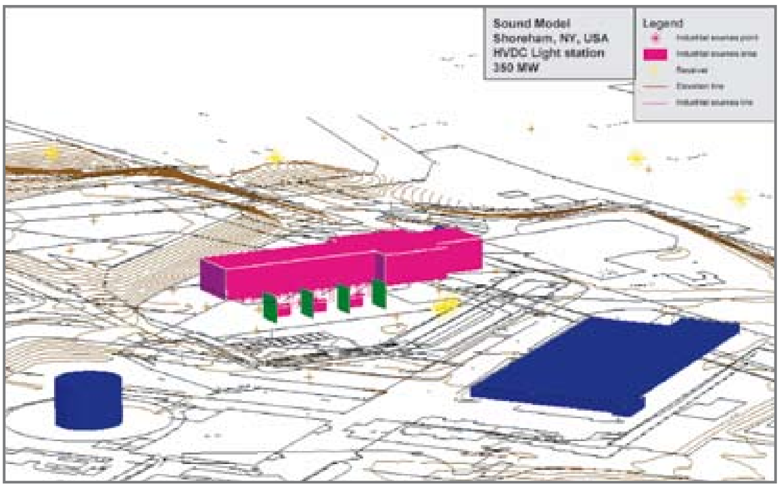
The other system, the standby system, is running, but the "outputs" from that system are disabled.

If a fault is detected in the active system, the standby system takes over control, becoming the new active system. The faulty system (the previously active system) should be checked before being taken into operation as the standby system.

- System changeover

The system switchover commands can be initiated manually or automatically. The manual commands are initiated by a push-button in the active system, while the automatic commands are initiated by extensive internal supervision functions of the subsystems, or on a protection order.

The switchover commands are always initiated from the currently 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.



An example of a 3D model and a result map for a typical HVDC Light® station.

- Changeover from protections
Control problems may initiate protection actions. To improve the overall reliability performance of the HVDC Light® transmission by avoiding unnecessary trips in connection with control problems, some of the converter and pole protections initiate a fast changeover from the active to the standby control system. Before a trip order is issued from the DC protection system, a system changeover is performed if the fault type could have been caused by a control failure, and the inherent delay in such a changeover is acceptable. 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. To achieve proper coordination between block/trip orders, both time and level separation is used.

- Protection redundancy
Both AC and DC protection trip actions are active in both systems, but only some of the DC protections, i.e. those that may have been initiated due to a control problem, can order a changeover.

Both systems are equipped with identical protections fed from separate primary sensors where practically possible.

- Self supervision
Inadvertent trips are avoided as each system is provided with extensive self-supervision, which further enhances system security. Examples of methods for self-supervision are:

- Inherent supervision in measuring systems (e.g. DCCT, DCOCT).

- Comparison in the software between actually measured zero sequence components and zero sequence components calculated in the software in the case of three-phase current measurement.

- Duplicated inputs and comparison in the software.

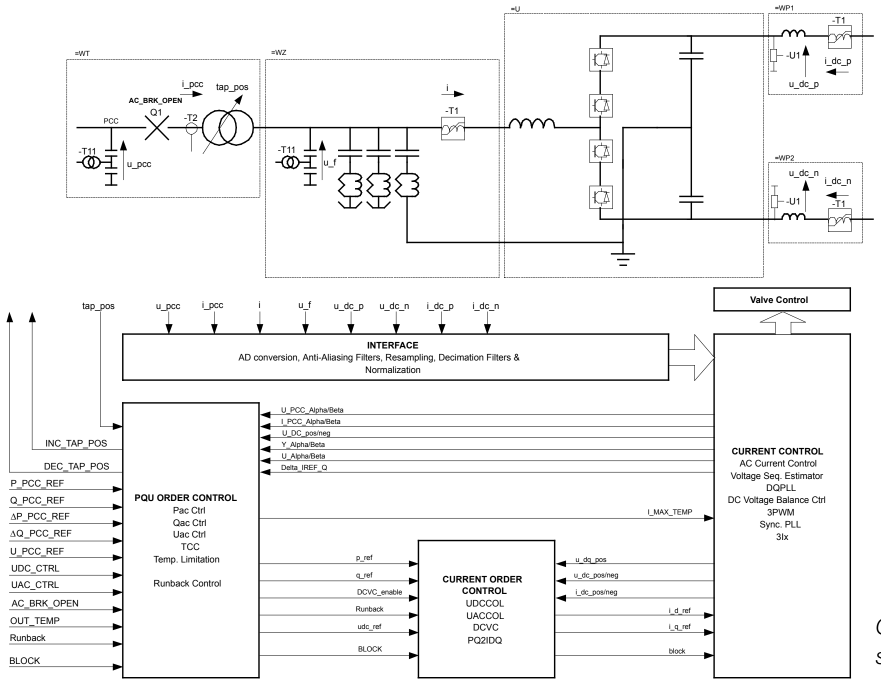
- Supervision of data bus communications.

- 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.

5.2.2 Converter control

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. The general control scheme of one converter station is shown in the figure below.



Control block diagram with simple Single-line diagram

5.2.3 Current control

The purpose of current control is to allow the current through the converter phase reactors and the transformer to be controlled. The control operates in a coordinate system phase synchronous to the fundamental frequency in the network, referred to as a dq-frame. The control reference object is the transformer current.

- Voltage sequence decomposition
The voltage sequence decomposition provides the true positive voltage sequence, u_dq_pos, for the phase-locked loop, the quasi-positive sequence, u_pcc_p, and the true negative sequence voltage, u_pcc_n, for the AC current control feed-forward voltages.

- DQPLL and SYNCPLL
The phase-locked loop (PLL) is used to synchronize the converter control with the line voltage. The input of the PLL is the three-phase voltages measured at the filter bus.

- AC current control
Controls the currents through the converter phase reactors and provides a symmetrical three-phase current to the converter, regardless of whether the AC network voltage is symmetrical or not. The current order is calculated from the power order.

- OPWM
The OPWM (optimal pulse width modulation) function must provide two functions: calculate the time to the next sample instant, and modulate the reference voltage vector. OPWM is a modulation method that is used for harmonic elimination and for reducing converter losses. The harmonic elimination concentrates the harmonics to a narrow bandwidth, which is beneficial for the filter design. Thus, the filters can be made smaller. The converter losses are reduced by switching the valves less frequently when the current is high. Using pulse width modulation makes it possible to achieve rapid control of the active and reactive power. This is beneficial when supporting the AC network during disturbances. The control is optimized to have a rapid and stable performance during AC system fault recovery.

5.2.4 Current order control

The current order control provides the reference current for the current control and acts as an interface between the PQU order control that operates on RMS values and the momentary control signals within the current control.

- DCVC and UDCCOL
The DC voltage control provides control of the DC voltage using the current order.

- UACCOL
The AC voltage-dependent current order limiter provides control to keep the AC filter bus voltage within its upper and lower limits.

- PQ2idq
The pq2idq calculates the dq current orders with respect to the positive-sequence voltage.

5.2.5 PQU order control

The PQU order control object must mainly calculate and provide the current order control block with active and reactive power references.

- Active power control/frequency control
The active power control controls the active power flow by generating a contribution to the DC voltage reference depending on the active power reference. In isolated mode, the frequency control will control the frequency of the isolated network.

- Reactive power control
The reactive power control controls the reactive power.

- AC voltage control
The AC voltage control controls the AC voltage.

- Tap changer control
The tap changer control is used to keep the filter bus voltage, and thus the modulation index, within suitable limits.

5.2.6 Protections

- Protection system philosophy

The purpose of the protection system is to cause a prompt removal of any element of the electrical system from service in the event of a fault, for example when it suffers a short circuit or when it starts to operate in any abnormal manner that might cause damage or otherwise interfere with the effective operation of the rest of the system. 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, thereby eliminating the DC current and voltage.

The protection system has extensive self-supervision. Any failures detected in the control and protection hardware result in appropriate actions depending on the severity of the fault. Failures may result in a request for changeover to the redundant system, which is executed if there is a standby system ready to take over.

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

- Transient current limitation by means of temporary blocking of the converter control pulses on a per phase basis
- Permanent blocking of the converter
- Tripping of the AC circuit-breakers

- Protective actions and effects

Alarms

Alarms are generally generated as a first action by some protections to notify the operator that something is wrong, but the system will still continue to run as before the alarm.

Transient current limiter

The transient current limiter stops sending pulses to the IGBTs corresponding to the phase with high current. The pulses are re-established when the current returns to a safe level (i.e. temporary blocking on a per phase basis). Overvoltage protection temporarily stops the pulses in all three phases simultaneously.

Permanent blocking

Permanent blocking means that a turn-off control pulse will be sent to all IGBTs and they will stop conducting immediately.

AC circuit-breaker trip

Tripping of the AC circuit-breaker disconnects the AC network from the converter equipment.

This prevents the AC system from feeding a fault on the valve side of the converter transformer.

In addition, the removal of the AC voltage source from the converter valves avoids unnecessary voltage stresses, especially when the valves have suffered severe current stresses.

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 checked the cause of the trip. The operator can manually reset the lockout of the breaker.

Pole isolation

The pole isolation sequence involves disconnecting 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 in the case of faults which require that the DC side is disconnected, for example a cooling water leakage.

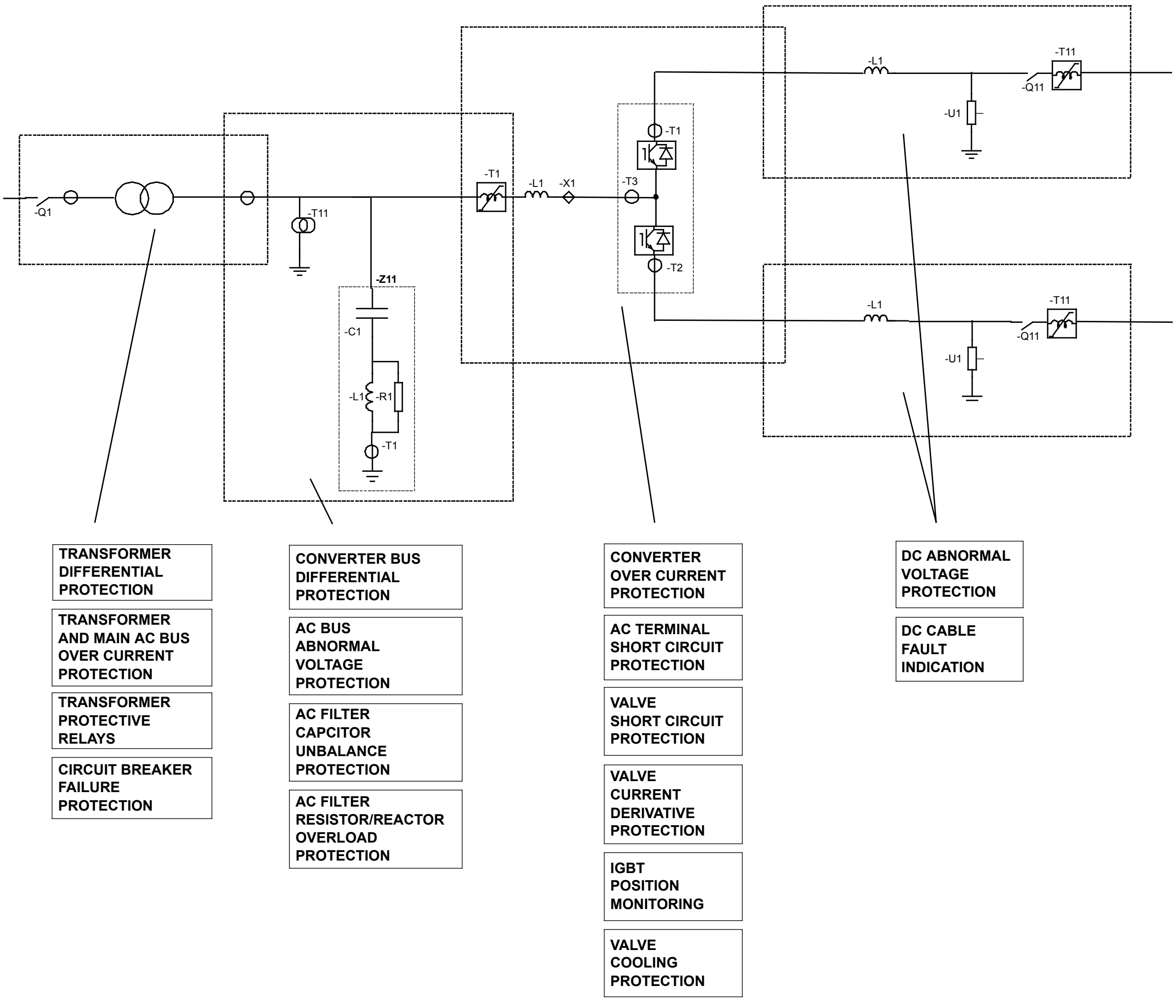
Start breaker failure protection

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 re-tripping and/or tripping of the next breaker.

Protection overview

The figure below shows the protections included in an HVDC Light® station

PROTECTION OVERVIEW



5.3 Control and protection platform - MACH 2

5.3.1 General

To operate a conventional HVDC or an HVDC Light® transmission as efficiently and flexibly as possible, a powerful, flexible and reliable control and protection system is clearly required. The control system should not impose any limitations on the control of the main system apparatus, such as the converter valves, and should not prevent the introduction of new, advanced, control and protection functions.

To fulfill the current and future requirements of the HVDC and HVDC Light® control and protection system, ABB has developed a fully computerized control and protection system using state-of-the-art computers, micro-controllers and digital signal processors connected by high-performance industrial standard buses and fiber optic communication links.

The system, called MACH 2, is designed specifically for converters in power applications, meaning that many compromises have been avoided and that both drastic volume reductions and substantial performance improvements have been achieved.

All critical parts of the system are designed with inherent parallel redundancy and use the same redundancy and switchover principles as used by ABB for HVDC applications since the early 1980s.

Because of the extensive use of computers and micro-controllers, it has been possible to include very powerful internal supervision, which will minimize periodic maintenance for the control equipment.

As a consequence of placing all functions in computers and micro-controllers, the software will play the most important role in the design of the system. 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. This is assured by careful component selection, strict design rules and, finally, by he extensive testing of all systems in a real-time HVDC simulator.

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

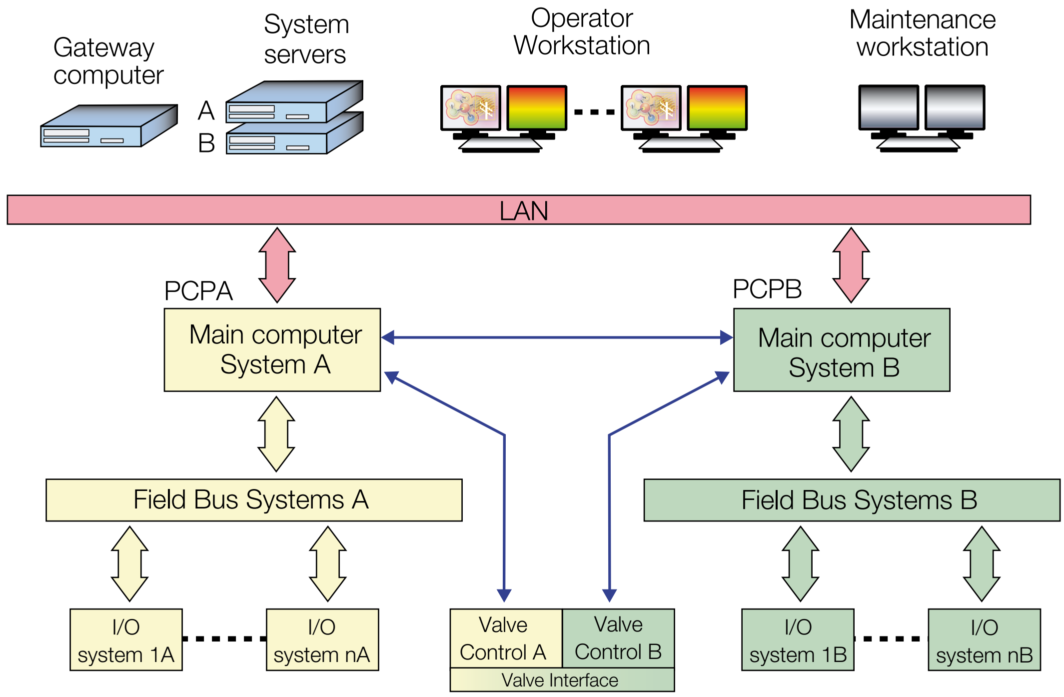
5.3.2 Control and protection system design

The HVDC Light® Control and protection system, built with the MACH 2 equipment, consists of HMI, main computer systems, I/O systems and valve control (valve base electronics), typically arranged as shown in the figure below.

The design criterion for the control system is 100% availability for the transmission system. The way to achieve this is that no single point of failure should interrupt operation. Therefore, redundancy is provided for all system parts involved in the power transfer of the HVDC Light® transmission.

The redundant systems act as active or hot standby. At any time, only one of the two control 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. If a fault is detected in the active system, the standby system takes over control, becoming the active system. The internal supervision giving switchover orders includes auxiliary power supervision, program execution supervision (stall alarm), memory testing and supervision of the I/O system communication over the field buses. The special ABB feature of using appropriate protections for switchover between systems further increases the control system reliability.

Thanks to the high performance of the MACH 2 equipment, the type of hardware and system software used for an ABB HVDC Light® control system are the same as in a classic HVDC control system. In fact, only the application software differs. This is also the case with the valve control (valve base electronics), including the communication to the IGBT firing unit, although a more advanced firing logic is needed for the IGBTs.



Mach 2 Control and Protection system structure

5.3.3 Main Computers

To take full advantage of the rapid electronic developments, the main computers of the Mach 2 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 micro-processors and always design the control and protection system for the highest possible performance.

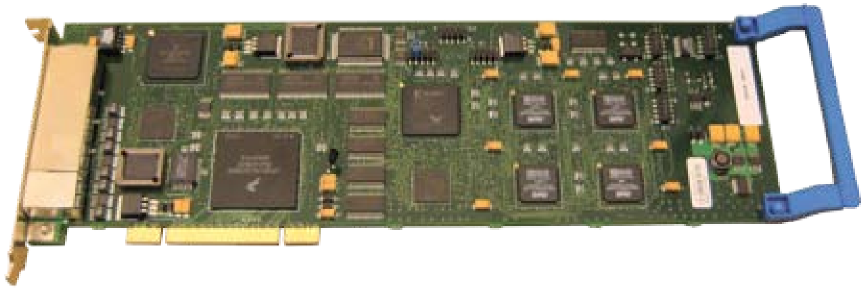
The main computers are built around COM Express modules with Intel® Core™ Duo processors, giving the main computers very good performance and, at the same time, very low power consumption. The low power consumption means that the main computers can be designed with self-convection cooling. Dust problems 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. The operating status of the computers/systems is clearly indicated on the front on all computers.

Main Computer

The main computers for control and protection include one ore more PCI boards, PS803, as an interface with the I/O system. The PS803 boards have a general-purpose processor and four DSPs for high-performance computing. Control and protection functions are normally running in the main computer, but the DSPs on the PS803 boards are used for high-performance applications. As an example, the firing control system, including converter sequences, runs in a single PS803 board.

The main computer may also include one or more measuring boards for optical current measurement.



High performance DSP board PS803

5.3.4 I/O system

The process interface of the redundant main computer systems is the I/O systems, placed in the control and protection cubicles or in separate cubicles or boxes. The field bus connections between the different levels of equipment (cubicles) are always optical to avoid any possible interference.

5.3.5 Communication

The communication inside the converter station uses a hierarchy of serial buses. A general rule for the use of serial buses is that only industry (or international) standard buses are used. This means that no proprietary buses are used. 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 well-known IEEE 802.3 (Ethernet).

• The SCADA LAN is used to transfer data between the control and protection main computers and the various clients on the network, OWS, GWS.

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.

• 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.

• CAN also have efficient CRC checksum 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. Fiber optic communications on eTDM are used for communication outside of the cubicles or control room.

Any application (software function) in a control, protection or I/O system can readily communicate with other applications, simply by connecting their signals respectively to send and receive software function blocks.

eTDM bus

The eTDM bus used in the Mach 2 system is primarily a high-speed, single fiber, optical data bus for digitized analog measurements. Due to the high-speed-performance of the bus, it has been possible to include the binary data from the CAN bus of the I/O systems as an “overlay” on the eTDM bus communication.

The eTDM bus used 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).

- 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 ISO3309 (HDLC frames) for high security.

If available, a LAN/WAN type of communication can also be used which 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 very common 1200, 2400 or 9600 bps communication links using analogue voice channels, up to digital 64 kbps or higher speed links obtained with optical fiber connections.

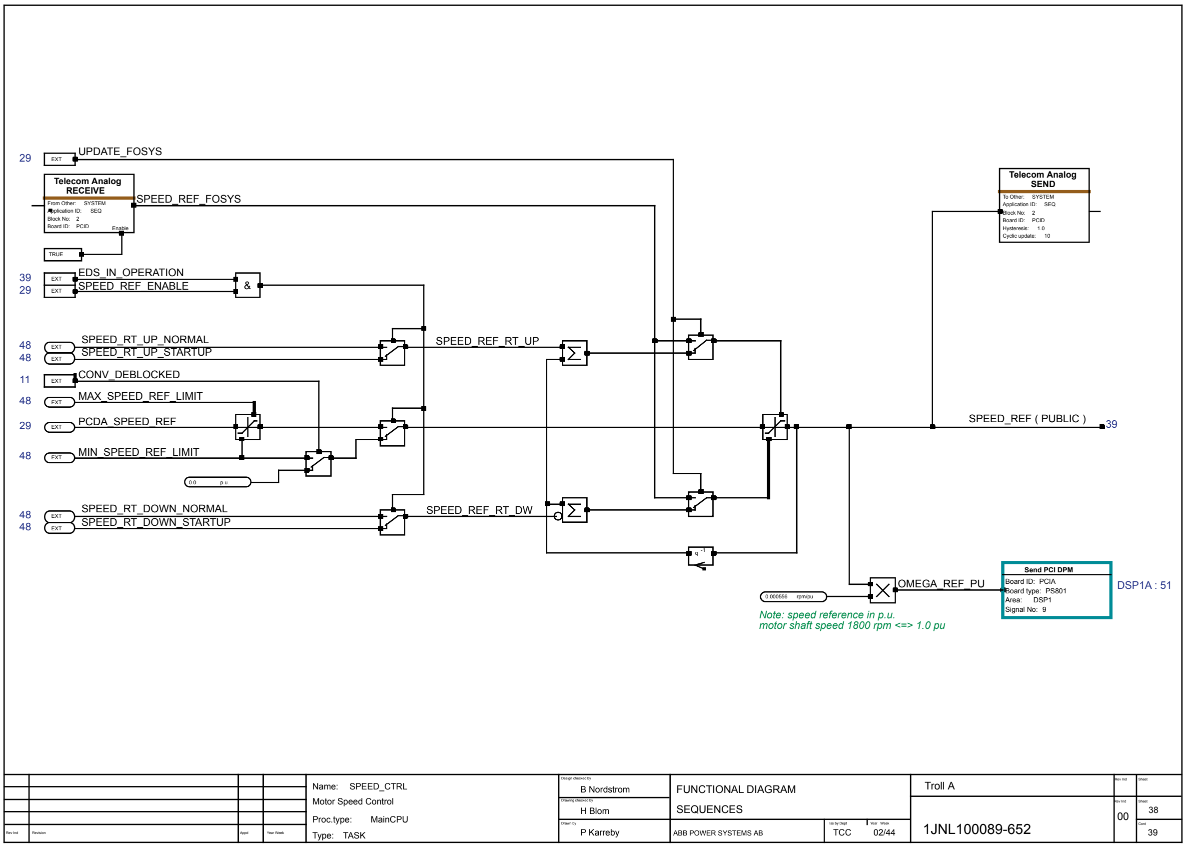
5.3.6 Software

- Application software development (HiDraw)

Most application software for the HVDC control and protection system is produced using a fully graphical code-generating tool called HiDraw. HiDraw is very easy to use, as it is based on the easiest possible drag-and-drop method. It is designed to produce code either in a high level language (PL/M or ANSI standard C) or in assembly language. For functions not available in the comprehensive library (one for each type of processor board), it is very easy to design a new block and to link this to the schematic with a simple name reference. HiDraw can be run on any industry-standard Windows-compatible computer.

A schematic drawn in HiDraw consists of a number of pages. One page specifies cycle times and the execution order of the other pages. HiDraw includes a first on-screen plausibility check of the drawn schematic and automatic cross-reference generation between the pages. As output, HiDraw produces code and a “make” file ready to be processed.

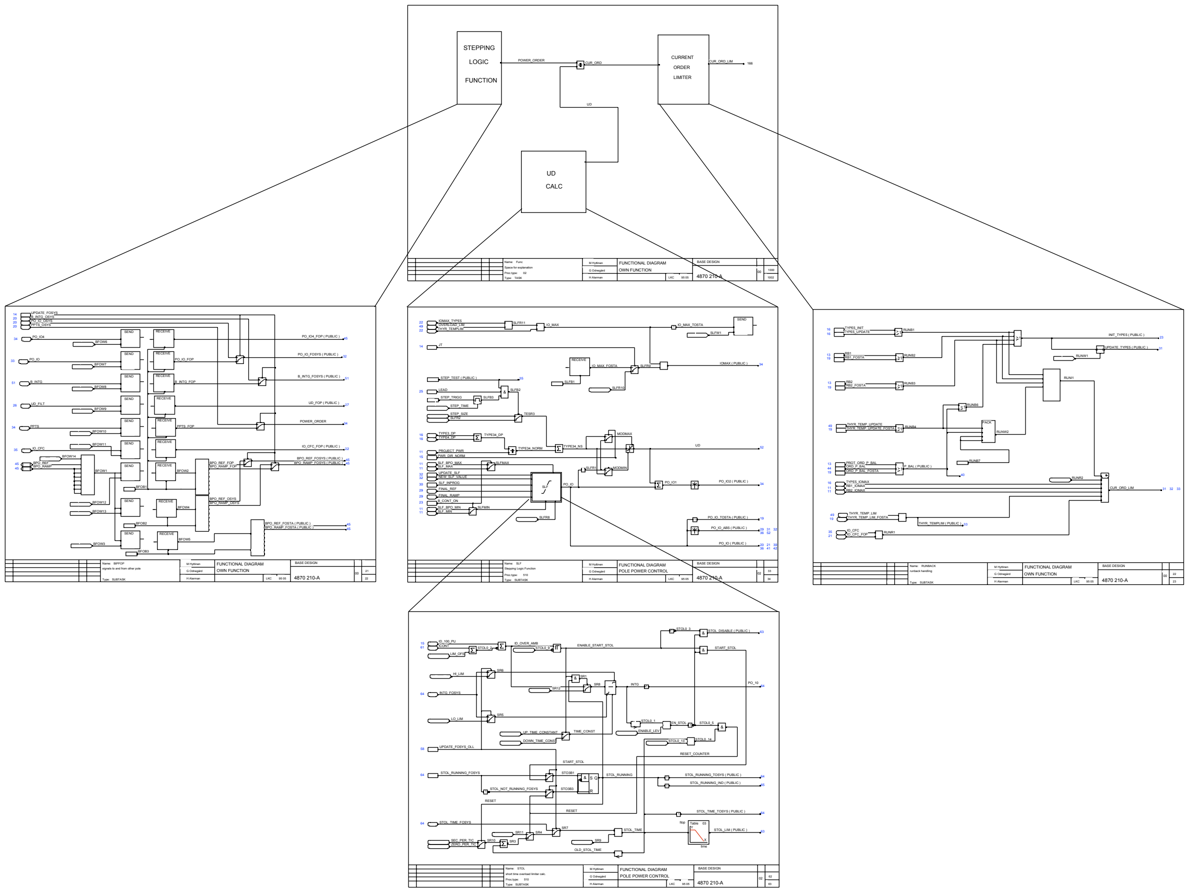
The next step in the workflow is to run this make file (on the same computer) which means invoking the necessary compiler/assembler and link locate programs (these are usually obtained from the chip manufacturers e.g. Intel and Analog Devices). The result is a file that is ready to be downloaded from the computer to the target and stored in the flash PROMs.



HiDraw schematic

- Hierarchical design

HiDraw supports hierarchical design in order to ease understanding of complex applications and to encourage top-down design. Hierarchical design means an organization of the drawings in a hierarchical structure, where symbols on the top layer represent functionality in rough outlines. Double-clicking on such a symbol opens a “hierarchical drawing” with more details of that symbol, etc. (see figure below).



Hierarchical symbols and drawings

5.3.7 Input to system studies

Code generation is performed by means of the code definitions in an HDF file (HDF = HiDraw Definition Format). Each graphical symbol in a symbol library has a name, and the name is used to define a piece of code in a separate HDF file. This open ABB approach is very advantageous in several aspects. One is from the HVDC Light® system point of view. The HiDraw drawings for control and protection, with the normal definition files producing code in C, PL/M, or DSP-assembler, are used simply by switching the definition files used to generate FORTRAN code.

The electromagnetic transient program PSCAD (previously PSCAD (previously EMTDC) can use this FORTRAN code directly, and an exact representation of the control and protection functions is thus achieved in the digital system studies.

5.3.8 Debugging facilities

For debugging, a fully graphical debugger, known as HiBug, operating under Windows is used.

HiBug allows the operator to view several HiDraw pages at the same time and look at any internal software "signal" in real time simply by double-clicking on the line that represents the signal. Parameters can be changed easily by double-clicking on their value.

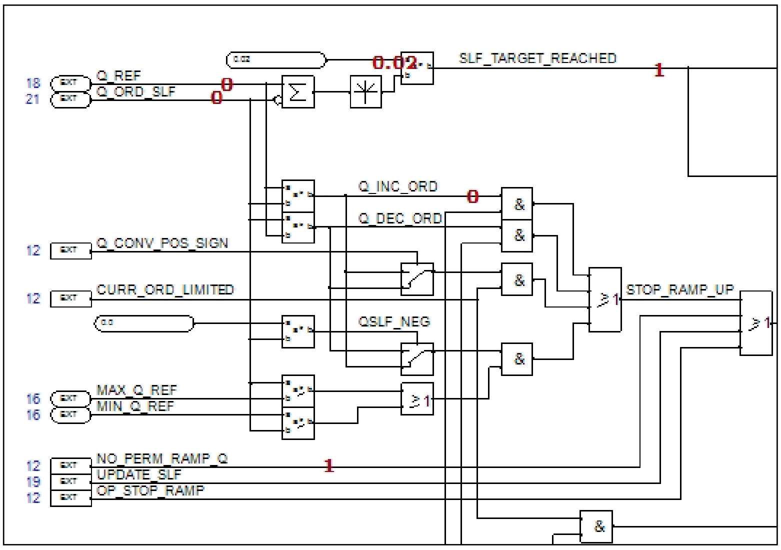
For fault tracing, it is easy to follow a signal through several pages because when a signal passes from one page to another, a double click on the page reference automatically opens the new page and allows the trace to continue immediately on the new page.

There are also a number of supporting functions, such as single or multiple stepping of tasks (one HiDraw page is normally a task) and coordinated sampling of signals.

The fact that HiBug allows inspection of signals while the application system is running makes it very useful not only for debugging but also to facilitate maintenance.

Because the debugger works in the Windows environment, it is also possible to transfer sets of signal values to other Windows-compatible programs, such as Excel, for further analysis.

All these development and debug tools are, of course, supplied to all customers of our plants, to facilitate their maintenance and future improvements of their HVDC Light® control and protection systems.



HiBug

5.3.9 Human-machine interface (HMI)

A well-designed and flexible human-machine interface (HMI) is clearly essential when it comes to more demanding application areas such as HVDC Light® power transmission. To avoid human errors, all parts of these systems must also be easy to use. The HMI must be able to announce alarms and perform operator controls in a safe and reliable way. Incorrect operator actions due to a bad HMI are not acceptable and could be very costly.

The requirements for tools of this type are therefore strict. 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 with high-time resolution for accurate real-time and post-fault analysis. Time resolution down to one millisecond between the stations is often required.

The new generation of integrated HMIs adopted by ABB in MACH 2™, the station control and monitoring (SCM) system, employs the most advanced software concepts with regard to system openness and flexibility, as well as ergonomic aspects. A number of power companies have made valuable contributions to this work.

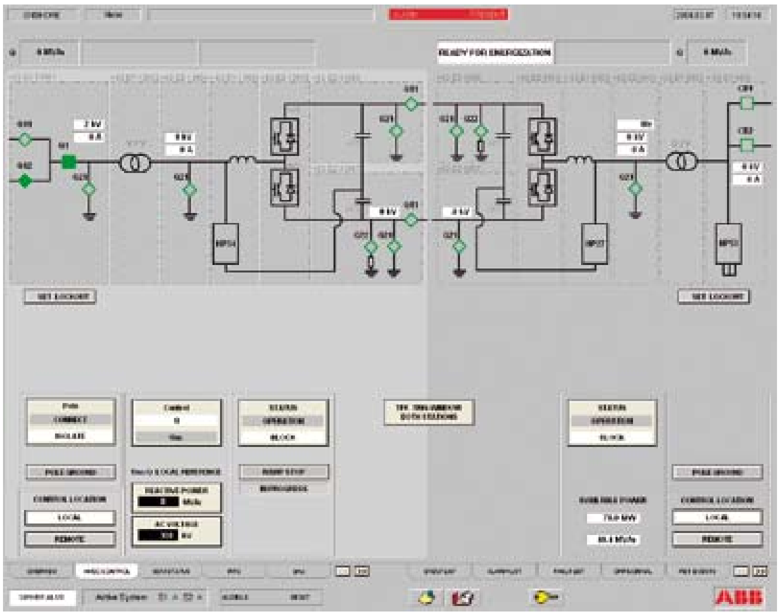
Distributed over an Ethernet LAN, the SCM system comprises several operator workstations (OWSs) and SQL servers. The Windows NT based OWSs are characterized by high performance and an open software architecture based on the latest trends in data engineering supporting TCP/IP, SQL and OPC.

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

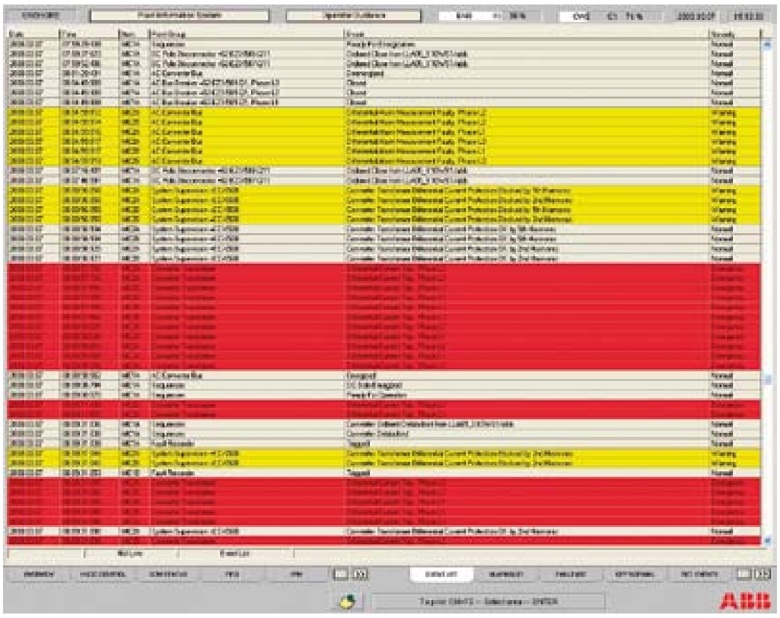
- Control of the HVDC Light® from process images, see the figure below
- Sequential Event Recorder, SER,

See the figure below

- 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
- TFR analysis
- Remote control via Dispatch Gateway
- Instant access to standard applications such as e-mail, word processing, spreadsheet, Internet
- Automatic performance report generation developed with the most versatile graphical package



SLD for a typical HVDC Light® station



Event list

5.3.10 Maintenance of MACH 2

- General
As far as possible, the ABB control equipment is built to avoid periodic maintenance and provide the shortest possible repair times. Due to its redundant design, the maintenance of the control equipment does not require any periodic shutdown of any main circuit equipment.

Maintenance is minimized by the extensive use of self-supervision built into all microprocessor-based electronic units and the ability to check all measured values during operation without disturbing the operation.

The internal supervision of microprocessor-based systems includes auxiliary power supervision, program execution supervision (stall alarm), memory test (both program and data memory) and supervision of the I/O system communication over the field buses.

The operation of the field buses is monitored by a supervisory function in the pole control and protection system, which continuously writes to and reads from each individual node of the system. Any detected fault results in an alarm and switchover to the standby system.

Another example of integrated self-supervision is the switch control unit. In this unit, the outputs to the breakers, etc., are continuously monitored to detect failure of the output circuits of the board. Very short repair times are facilitated by the self-supervision, but another contribution to this is the high degree of integration in all units. As an example, the entire control computer, including the converter firing control system, etc., is easily changed in a couple of minutes, as the whole system is a single-rack unit with only a handful of connection cables.

- Transient fault recorder (TFR)
The TFR integrated in the HVDC control system, as a part of the control and protection software, is an invaluable tool for maintenance and out-performs 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. Important external signals can, of course, also be connected for monitoring by the TFR.

As the TFR is an integrated part of the HVDC control system, it also runs in both the active and the standby systems.

Any standard software analysis program interpreting the COMTRADE format, (IEEE C37.111-1991), can be used for post-fault analysis of the stored TFR records.

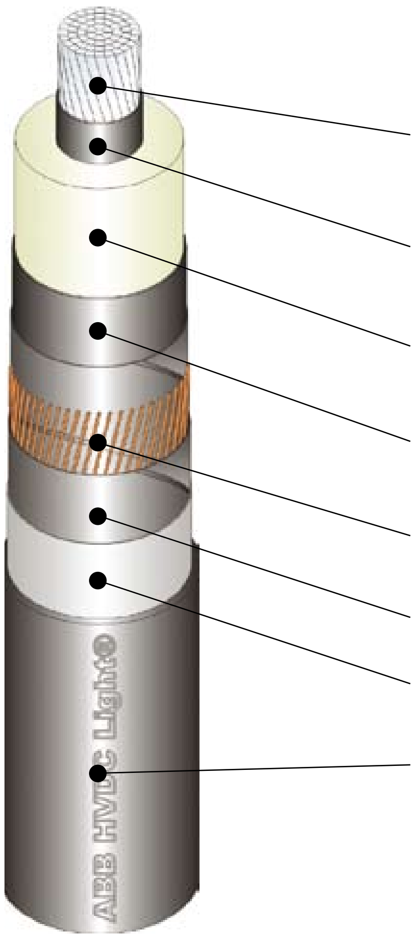
5.4 HVDC Light® Cables

5.4.1 Design

The cables are designed to meet the current and voltage ratings for the specified power transmission capacity and for the specified installation conditions.

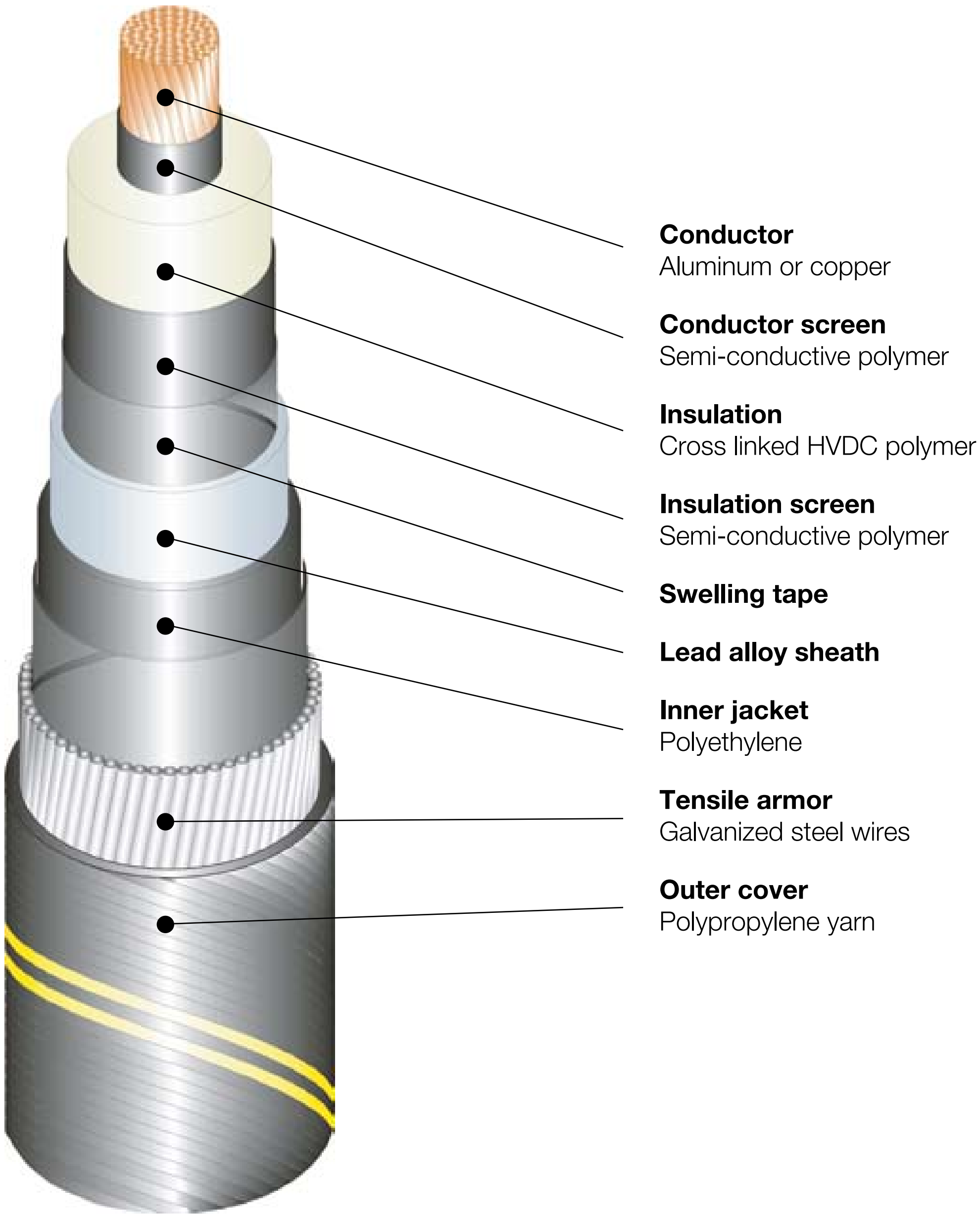
5.4.2 Land cable

A general cutaway drawing of the land cable design is shown below



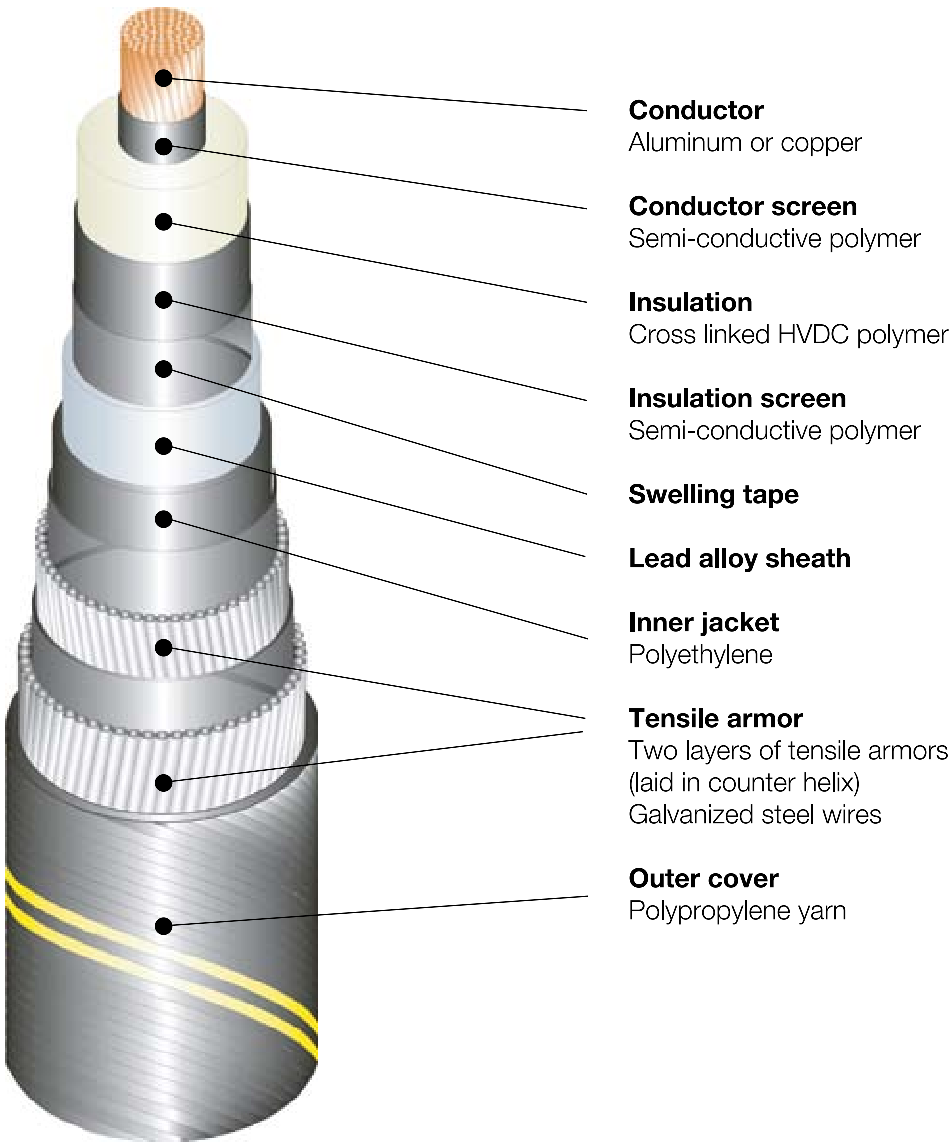
5.4.3 Submarine cable

A general cutaway drawing of the submarine cable design is shown below



5.4.4 Deep-sea submarine cable

A general cutaway drawing of the deep-sea submarine cable design is shown below



5.5 General design of cables

Typical HVDC Light® cable designs are previously shown.

5.5.1 Cable parts

- 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 longitudinally water penetration 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.

5.5.2 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 over-sheaths 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

5.5.3 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	LIPL kV	U_{P1} kV	SIPL kV	$U_{P2,S}$ kV	$U_{P2,O}$ kV
80	148	116	160	185	143	165	92
150	278	217	304	350	275	320	175
320	555	435	573	660	541	630	350

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_{P1} Lightning impulse voltage > 1.15LIPL. Not applicable for HVDC Light® System.

$U_{P2,S}$ 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.

5.5.3.1 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	2
320	1200	2
	Total	28

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 $U_{P2,O}$

5.5.3.2 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

5.5.3.3 Post-installation test

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

For land cables also:

DC-testing on non-metallic sheath, according to IEC 60229

5.5.4 Cable drums

Land cables are typically transported on cable drums.

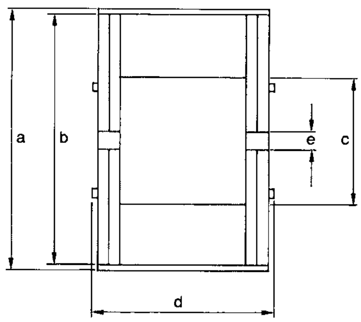
Cable lenghts in metres on Wooden drum K14 - K30 and Steel drum St 28 - St 34

Cable dia.	Wooden drum									Steel drum										
mm	K14	K16	K18	K20	K22	K24	K26	K28	K30	St 28	St 30	St 32	St 34	St 35	St 36	St 37	St 38	St 39	St 40	St 43
36	570	760	850	1155	1560	2090	2860	4000	5800	4600	6080	7670	9350	9930	11130	11750	13000	13600	14900	17700
38	470	630	820	1075	1290	1780	2490	3600	4900	4300	5335	6830	8420	8970	10110	10700	11200	12500	13100	15700
40	450	610	690	900	1100	1560	2220	3200	4400	3700	5085	6030	7530	8050	9130	9680	10250	11400	12000	14500
42	430	500	660	870	1070	1510	2160	3100	3950	3600	4485	5850	6820	7320	8350	8880	9400	9900	11100	12900
44	340	480	530	720	1030	1310	1830	2800	3900	3000	3830	5100	6000	6475	7400	7940	8450	8900	9500	11740
46	330	450	510	690	860	1260	1780	2430	3460	2900	3695	4500	5800	6260	6720	7200	7690	8100	8600	10840
48	310	360	480	660	820	1070	1540	2360	3130	2450	3175	4340	5170	5600	6040	6490	6950	7400	7900	9960
50		360	400	550	670	1020	1490	2090	2820	2410	3120	3880	4670	5090	5520	5960	6410	7300	7800	9330
52		340	385	530	670	910	1280	1830	2750	2300	2990	3720	4490	4890	5300	6730	6165	6600	7060	8500
54		320	360	505	640	870	1280	1775	2450	1880	2520	3200	3920	4300	4680	5080	5490	5900	6340	7690
56		260	360	475	610	825	1090	1715	2380	1840	2470	3130	3850	4220	4600	5600	4990	5400	5810	7120
58		240	275	385	510	720	1040	1550	2090	1800	2410	2740	3410	3775	4140	4510	4900	5300	5710	6560
60			275	365	480	680	990	1490	2030	1760	2050	2680	3340	3690	4050	4050	4430	4800	5200	6450
62			250	365	480	680	460	1270	1770	1390	1940	2540	2850	3170	3500	3850	4200	4570	4570	5730
64			250	345	450	545	825	1270	1730	1350	1890	2180	2780	3100	3420	3420	3675	4100	4470	5220
66			240	345	370	545	825	1230	1535	1320	1575	2125	2710	2710	3020	3340	3675	4000	4010	5100
68			240	320	345	515	785	1025	1475	1280	1530	2060	2340	2640	2940	3250	3250	3580	3910	4610
70				250	345	515	670	1030	1475	1280	1530	2060	2340	2640	2940	2960	3250	3600	3910	4610
72				250	345	480	635	985	1260	1010	1490	1750	2290	2290	2580	2880	3190	3190	3510	4190
74				250	320	400	635	985	1260	980	1440	1690	1950	2230	2510	2800	2800	3100	3420	4080
76				230	320	400	625	810	1210	940	1170	1640	1890	2160	2430	2430	2720	3000	3010	3630
78				230	320	400	600	810	1210	910	1130	1590	1830	2090	2090	2350	2635	2635	2920	3520
80					230	325	500	810	1015	910	1130	1360	1830	1840	2090	2350	2370	2635	2920	3520
82					230	325	470	775	1015	885	1090	1310	1540	1780	2030	2030	2295	2560	2560	3140
84					210	300	470	660	1015	880	1090	1310	1540	1780	2030	2030	2295	2310	2560	3140
86					210	300	470	615	965	660	1050	1270	1490	1720	1720	1970	2220	2220	2495	3050
88					210	275	440	615	840	630	820	1220	1430	1430	1660	1890	1890	2140	2140	2670
90					210	275	440	615	840	630	820	1220	1430	1430	1660	1670	1890	2140	2140	2670
92							355	585	800	610	785	970	1380	1380	1600	1600	1835	1835	2070	2580
94							325	585	800	610	785	970	1180	1380	1390	1600	1835	1835	2070	2340
96							325	485	755	585	755	930	1130	1330	1330	1540	1540	1760	1760	2240
98							325	485	640	580	755	930	1130	1330	1330	1540	1540	1760	1760	2240
100							325	455	640	580	755	930	1130	1140	1330	1340	1540	1760	1760	2240
102										560	725	900	1080	1080	1280	1280	1490	1490	1710	1930
104										560	725	900	1080	1080	1280	1280	1490	1490	1710	1930
106										385	530	690	860	1040	1040	1230	1230	1430	1430	1860
108										380	530	690	860	1040	1040	1230	1230	1430	1430	1860
110										380	530	690	860	1040	1040	1230	1230	1430	1430	1860
112										365	505	660	820	990	990	990	1180	1180	1370	1570
114										360	505	660	820	820	990	990	1180	1180	1370	1570
116										360	505	660	820	820	990	990	1180	1180	1370	1570
118										345	480	625	785	780	950	950	1120	1120	1120	1500
120										340	480	625	785	780	950	950	950	1120	1120	1500
122										340	480	625	785	780	790	950	950	1120	1120	1320
124										325	450	595	595	740	740	900	900	1070	1070	1250
126										325	450	595	595	740	740	900	900	900	1070	1250
128										325	450	450	595	740	740	750	900	900	1070	1250
130										325	450	450	595	740	740	750	900	900	1070	1250
132										305	305	430	560	560	700	700	850	850	850	1190
134										305	305	430	560	560	700	700	850	850	850	1190

Sizes and weights of wooden drums										
		Drum type								
		K14	K16	K18	K20	K22	K24	K26	K28	K30
Shipping volume	m³	2.14	2.86	3.58	5.12	6.15	7.36	10.56	13.88	17.15
Drum weight incl. battens	kg	185	275	320	485	565	625	1145	1460	1820
a Diameter incl battens	mm	1475	1675	1875	2075	2275	2475	2700	2900	3100
b Flange diameter	mm	1400	1600	1800	2000	2200	2400	2600	2800	3000
c Barrel diameter	mm	800	950	1100	1300	1400	1400	1500	1500	1500
d Total width	mm	982	1018	1075	1188	1188	1200	1448	1650	1800
e Spindle hole diameter	mm	106	106	131	131	131	131	132	132	132

Sizes and weights of steel drums												
		Drum type										
		St 28	St 30	St 32	St 34	St 35	St 36	St 37	St 38	St 39	St 40	St 43
Shipping volume	m³	20.6	23.5	26.6	28.9	31.6	33.4	35.2	37	38.9	40.9	47.1
Drum weight incl. battens	kg	1500	1700	2200	2600	2700	2800	3000	3100	3300	3500	4000
a Diameter incl battens	mm	2930	3130	3330	3530	3630	3730	3830	3930	4030	4130	4430
b Flange diameter	mm	2800	3000	3200	3400	3500	3600	3700	3800	3900	4000	4300
c Barrel diameter	mm	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
d Total width	mm	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400
e Spindle hole diameter	mm	150	150	150	150	150	150	150	150	150	150	150

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.



a Diameter incl. battens
b Flange diameter
c Barrel diameter
d Total width
e Spindle hole diameter

5.5.5 Installation

- 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 trenchless technologies including directional drilling, pipe jacking and others.

- 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

5.5.6 Repair

- Fault Location
It is important to perform a fairly fast pre-location of a fault for the repair planning. The converter protections identify the cable that is faulty. If possible, the pre-location could start with an analysis of the records in the converter stations in order to give a rough estimate the location of the fault.

- Pre-location of fault with pulse echo meter or fault location bridge
A fault in the HVDC cable is pre-located 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 forth and back 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 the fault location bridge should give approximately the same distance to the fault as the TDR.

- Accurate location of a fault
The principle for this method is to use the 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.

5.5.7 Accessories

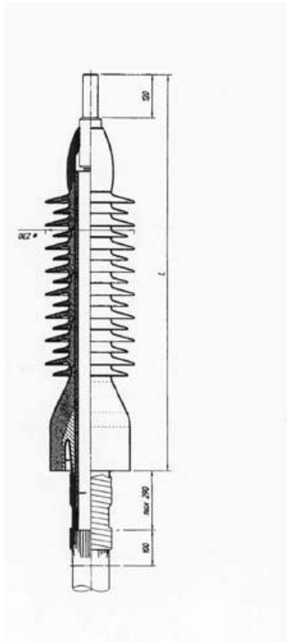
The only accessories required for HVDC Light® cable systems are cable joints and terminations.

- 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.

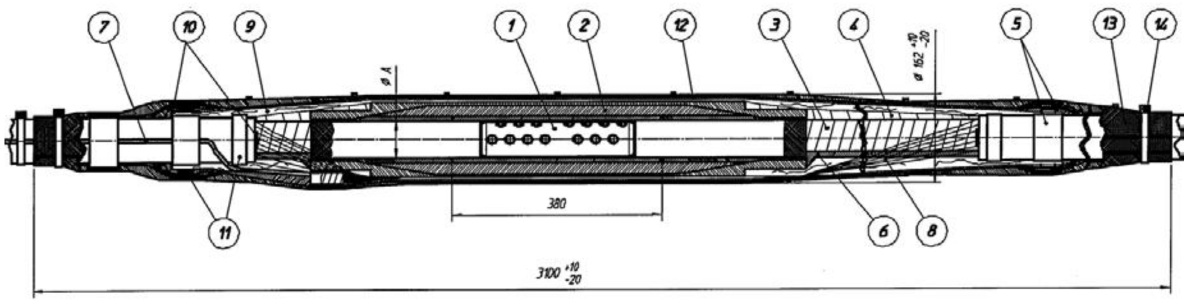
- Cable joints
Joints for HVDC Light® are based on field molding or pre-fabricated joint techniques.

The field molding method uses a mini process to restore the insulation, and it gives a joint with the same diameter as the cable.

Pre-fabricated joints are used to connect the cables. The design involves a screwed conductor connector and a pre-fabricated 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 pre-testing of the joint bodies.



Cable termination for 150 kV HVDC Light® cables.



Pre-fabricated 150 kV HVDC Light® cable joint.

5.5.8 Auxiliary equipment

Other auxiliary equipment may be used for the cable system, e.g.:

- Cable Temperature Sensing Systems
- Forced Cooling Systems

5.5.9 Environmental

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.

5.5.10 Reliability of 150 kV HVDC Light® Cable projects

Cross Sound Submarine Cable, Connecticut – Long Island

83 km	HVDC Light® Cables with 1300 mm^2 copper conductor
7 pcs	Flexible Cable Joints
4 pcs	Cable Terminations
Delivery year	2002.

Operating experience very satisfactory. No faults.

MurrayLink Land Cable, Victoria – South Australia

137 km	HVDC Light® Cables with 1400 mm2 aluminum conductor
223 km	HVDC Light® Cables with 1200 mm^2 aluminum conductor
400 pcs	Stiff Cable Joints
4 pcs	Cable Terminations
Delivery year	2002

Operating experience very satisfactory. One fault attributed to external damage.

6 System Engineering

6.1 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 the PSS/E simulation tool. For unusual applications, ABB can perform feasibility studies using a detailed control representation in PSCAD (previously EMTDC).

For new applications, it is advisable that ABB performs pre-engineering studies, which include main circuit design, system performance and station layout design.

6.2 System design

A suitable rating of converters and DC cables is determined to satisfy the system requirements. The HVDC Light® system is adapted to fulfill the requirements for the project. Some engineering work needs to be done to define the system solution, equipment and layout needed.

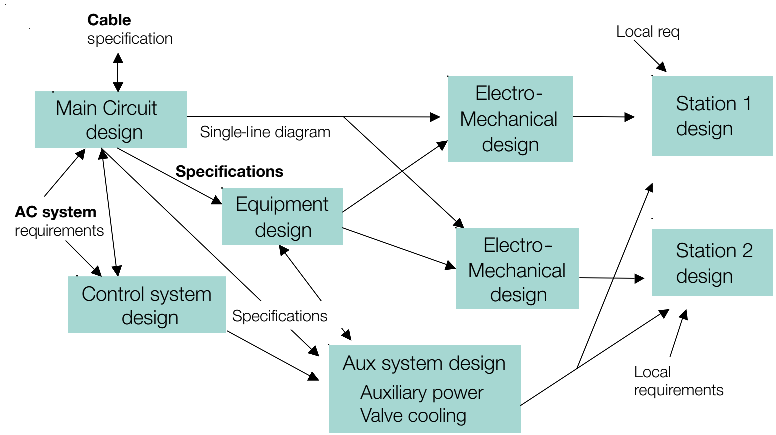
The flow diagram below illustrates the types of engineering required.

The main circuit design includes the following design studies:

- Main circuit parameters
- Single-line diagram
- Insulation coordination
- AC and DC filter design
- Radio interference study
- Transient overvoltages
- Transient currents
- Calculation of losses
- Availability calculation
- Audible noise study

The control system design specifies the requirements to be met by the control and protection system. During the detailed design, the control system characteristics are optimized to meet the requirements.

The equipment design specifies the requirements of all the main circuit apparatus. The rating includes all relevant continuous and transient stresses.



The auxiliary system design includes the design of auxiliary power, valve cooling, 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.

6.3 Validation

- DPS

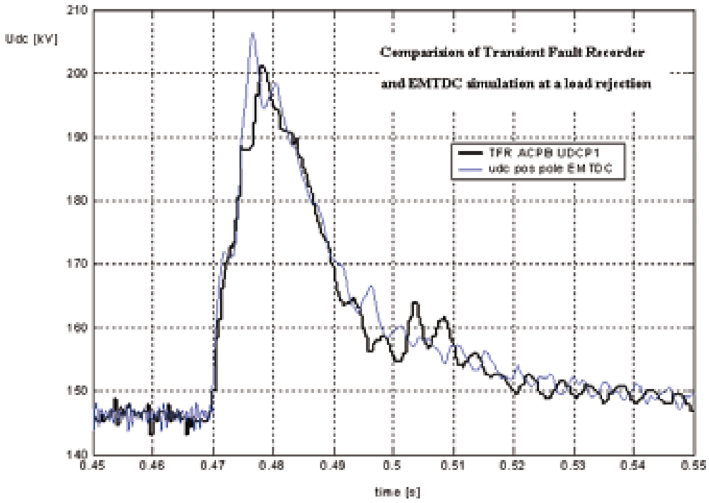
The performance of the combined AC and DC system is validated in a dynamic performance study (DPS). The setup includes a detailed representation of the main circuit equipment, and the control model is a copy of the code that will be delivered to site (see 5.3.7 above). The AC systems are represented with a detailed representation of the immediate vicinity and an equivalent impedance for the rest 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.



- Reference cases

The figure above shows a comparison between site measurement and PSCAD (previously EMTDC) simulation of the DC voltage at a load rejection of 330 MW. Even though the transient is fast, the behavior is quite similar.

6.4 Digital Models

- Load flow

During load flow calculations, the converters are normally represented with constant active power and a reactive power that is situated within the specified PQ-capability, in the same way as generators. A load flow model of a VSC HVDC transmission is included in the latest version of PSS/E.

- Stability

The dynamic model controls the active power to a set-point in one station and calculates the active power in the other station, including current limitations. The reactive power or the AC voltage is controlled independently in each station. ABB can supply dynamic models of HVDC Light® transmissions in the PSS/E simulation tool.

- Dynamic Performance

Detailed evaluation of dynamic performance requires an extensive PSCAD (previously PSCAD (previously EMTDC) model that can be supplied to the customer during the project stage.

7 References

7.1 Projects

Gotland HVDC Light® Project

Directlink HVDC Light® Project

Tjæreborg HVDC Light® Project

Eagle Pass HVDC Light® Project

Cross Sound Cable HVDC Light® Project

MurrayLink HVDC Light® Project

Troll A Precompression Project

Estlink HVDC Light® Project

Valhall Re-development Project

NordE.ON 1 offshore wind connection

Caprivi Link interconnector

7.2 Applications

HVDC Light® as interconnector

HVDC Light® for offshore

Wind power and grid connections

7.3 CIGRÉ/IEEE/CIRED material

DC Transmission based on VSC

HVDC Light® and development of VSC

VSC TRANSMISSION TECHNOLOGIES

HVDC Light® experiences applicable to power transmission from offshore wind power farms

Cross Sound Cable Project – second-generation VSC technology for HVDC

MurrayLink – the longest HVDC underground cable in the world

Power system stability benefits with VSC DC transmission system

New application of voltage source converter HVDC to be installed on the Troll A gas platform

The Gotland HVDC Light® project - experiences from trial and commercial operation

CIGRE WG B4-37-2004

7.4 General

For further material please refer to ABB HVDC Light® on the Internet:

http://www.abb.com/hvdc

8 Index