ABB review

The corporate technical journal

Special Report
60 years of HVDC

Power and productivity
for a better world™

60 years ago, ABB's predecessor company, ASEA, laid the cable for the world's first commercial HVDC subsea power link, Gotland 1, connecting mainland Sweden to the island of Gotland. This groundbreaking event was the beginning of the modern era of HVDC transmission. Today, ABB remains the market leader in HVDC and is the only company in the world that can supply the complete range of products for an HVDC system.

The picture here and on page 5 shows a cascaded two-level valve arm, rated at 320 kV DC, from the HVDC Light installation Dolwin1 in Germany.

Impact of HVDC

HVDC at work

Components of HVDC

Editorial

60 years of HVDC

Claudio Facchin
Head of Power Systems division

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Global Business Unit Manager,
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Dear Reader,

This year, we celebrate the 60th anniversary of the first commercial subsea high-voltage direct current (HVDC) power transmission link – a groundbreaking project that used mercury-arc converters and mass-impregnated high-voltage cables to bring electricity from mainland Sweden to the island of Gotland in the Baltic Sea. Over the course of 25 years, Dr. Uno Lamm and his team at ASEA had researched previously unexplored fields to overcome the challenges of HVDC transmission – work that culminated in the commissioning of the Gotland link in 1954. Since then, more than 170 HVDC projects have been installed around the world, bringing bulk power from distant locations to where it is needed.

HVDC is the technology of choice for transmitting power efficiently and reliably over long distances. It is ideally suited for integrating renewable energy sources situated in remote and challenging locations. The benefits of reliable, long-distance transmission with minimum losses, combined with features like the ability to connect unsynchronized power grids, have opened new opportunities for this versatile technology.

Classic HVDC power transmission technology has come a long way: from the first 20 MW, 100 kV transmission in Gotland to ultrahigh-voltage DC links like the 800 kV Hami-Zhengzhou transmission link in China, with a capacity of 8,000 MW. As part of this ongoing journey, ABB has developed new technologies – eg, line-commutated converters using thyristor-based HVDC valves (up to 1,100 kV) that make low-loss DC power transmission of 10 GW over distances up to 3,000 km viable.

A major advance came in the late 1990s, when ABB introduced HVDC Light. With well over a dozen projects completed, this technology is being successfully deployed in an increasing number of applications, thanks to the parallel development of higher converter voltage and power ratings, IBGT-based semiconductors, and extruded cables with solid polymer insulation. By embedding HVDC Light functionalities into an AC network, voltage support, reactive power compensation, black start, and the performance of existing grid assets can be reinforced.

HVDC connections are currently point-to-point, so a logical next step is to network them. This will optimize network reliability as well as enable balancing of loads, integration of intermittent renewables, lowering of transmission losses and energy trading across borders. The missing link here has always been a low-loss HVDC breaker that acts fast enough to interrupt current and isolate faults. ABB has now developed a solution for this century-old challenge.

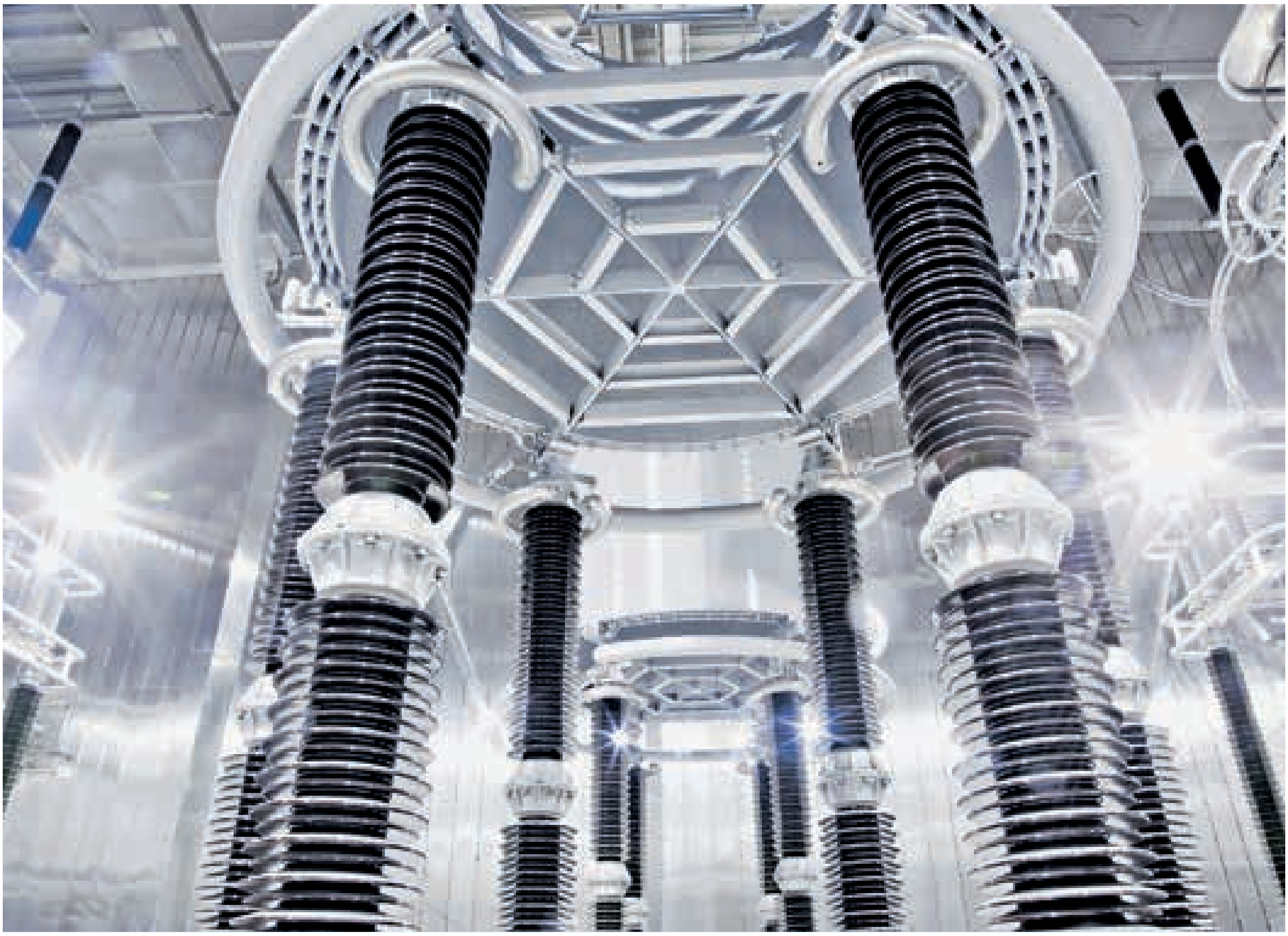
Today, ABB remains the market leader in HVDC, with more than half the global installed base and the unique distinction of being the only company in the world with in-house manufacturing of key components like converters, cables and semiconductors, as well as switchgear, transformers and products along the entire power value chain. This special edition of *ABB Review* showcases how ABB keeps its HVDC pioneering heritage alive by remaining at the forefront of this technology and continuing to shape the grid of the future.

Join us on this journey. Happy reading!

Claudio Facchin

Hanspeter Fässler


U03
U04

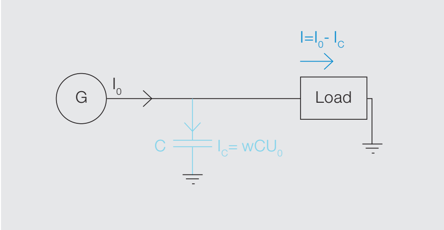


Powering the world

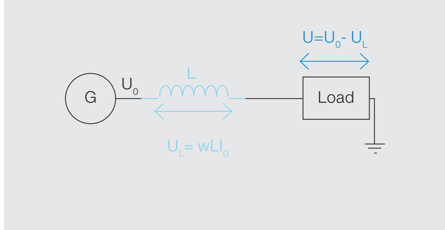
ABB is the global leader in HVDC transmission

MAGNUS CALLAVIK, MATS LARSSON, SARAH STOETER – The installation of the world's first commercial high-voltage direct current subsea power link, Gotland 1, in 1954 was the beginning of ABB's lifetime commitment to HVDC. Since then, generations of ABB engineers have, together with ABB's customers, pushed the envelope of HVDC technology, resulting in more powerful links at greater distances. Today, as much as 8,000 MW can be transmitted – the 2,210 km, ±800 kV Hami-Zhengzhou UHVDC link commissioned in early 2014 is one example. ABB has had many other firsts over the years, not least of which is the groundbreaking development of the world's first hybrid HVDC breaker, resolving the largest roadblock in the development of an HVDC grid. As more electricity is generated from renewable sources in remote areas and requires long-distance transmission, there is a greater push toward DC power. ABB, the only supplier to offer the complete range of products for an HVDC system, remains committed to HVDC.

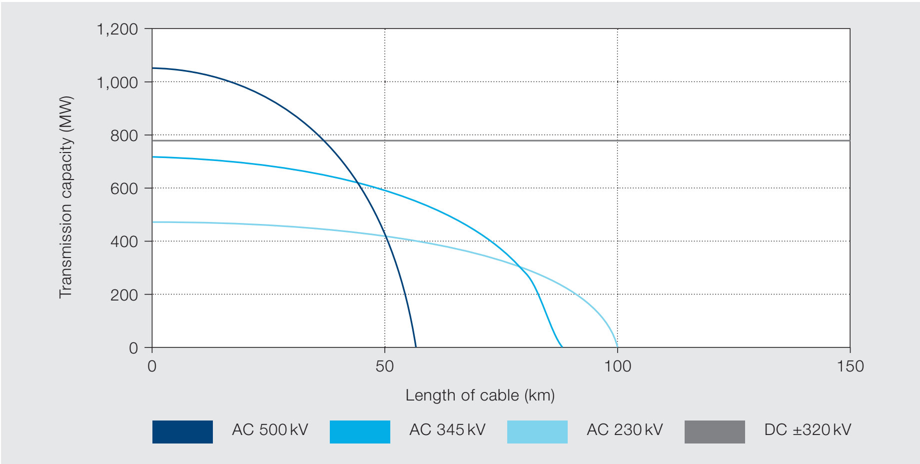
1 The limitations of AC transmission



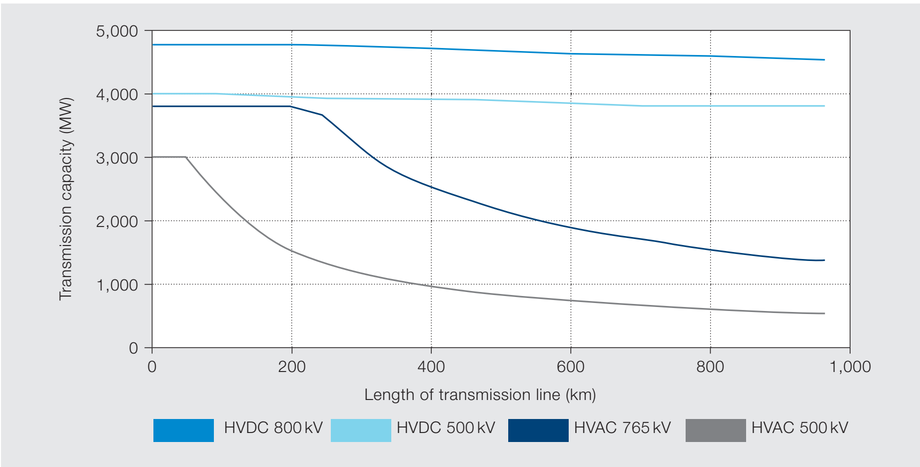
1a Underground cable



1b Overhead line



1c Transmission capacity of AC and DC with cables



1d Transmission capacity of AC and DC with overhead lines

Back in the early days of electricity supply, AC (alternating current) was adopted for power transmission because it could be stepped up or down as needed by transformers, and because it could be interrupted more easily than DC (direct current). High-voltage AC grids evolved as an efficient way to connect existing islands of distribution grids and large generation units with industrial and residential loads. It was not until some decades later that the technology for high-voltage DC (HVDC) power advanced sufficiently for the first commercial HVDC link to be established. The pioneering work by Uno Lamm at one of ABB's predecessor companies, ASEA, began in 1929 and resulted in the first subsea HVDC link using mercury-arc converter valves in 1954. Now, 60 years later, ABB has supplied, or has been a subsupplier to, more than 90 HVDC connections. The company has helped transform HVDC from being a relatively specialized application to a key technology enabling both low-loss, high-power connections between power markets and remote renewable generation.

Title picture
The new HVDC Light technology is increasingly being used as the power range increases and losses decrease. Shown here is the reactor hall for an HVDC Light installation at 320 kV.

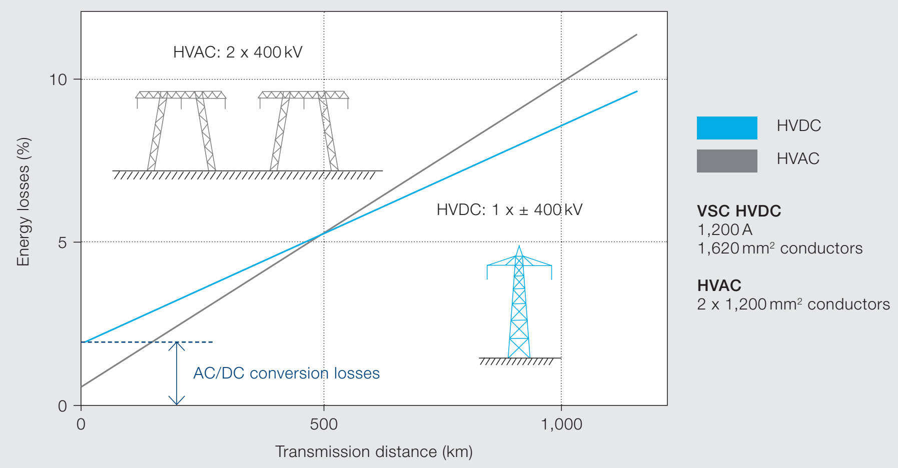
Why HVDC?

In DC, as opposed to AC, electrons flow through the circuit in one direction only, and, as a result, do not generate reactive power. AC cables have primarily capacitive characteristics → 1a, whereas overhead lines have primarily inductive characteristics → 1b. Long AC cables generate a lot more reactive power than they consume, and require a large reactive current to charge and discharge the cable as the grid voltage changes polarity 50 or 60 times per second. This current is added to the active current needed to transport the energy from one end of the cable to the other.

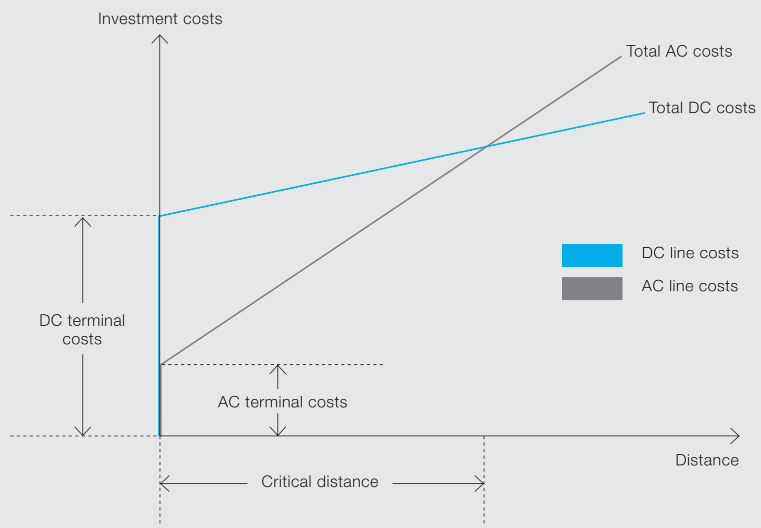
Both active and reactive current use the thermal capacity of the cable. Due to the generation of reactive power, high-voltage AC cable transmission links have a maximum practical length of about 50 to 100 km → 1. In underground cables longer than 50 km, most of the AC current is required to charge and discharge the capacitance (C) of the cable → 1a. In

ABB has supplied more than half of the world's HVDC connections.

2 DC power has lower losses on longer distances.



3 There is a critical distance at which DC becomes more cost effective.



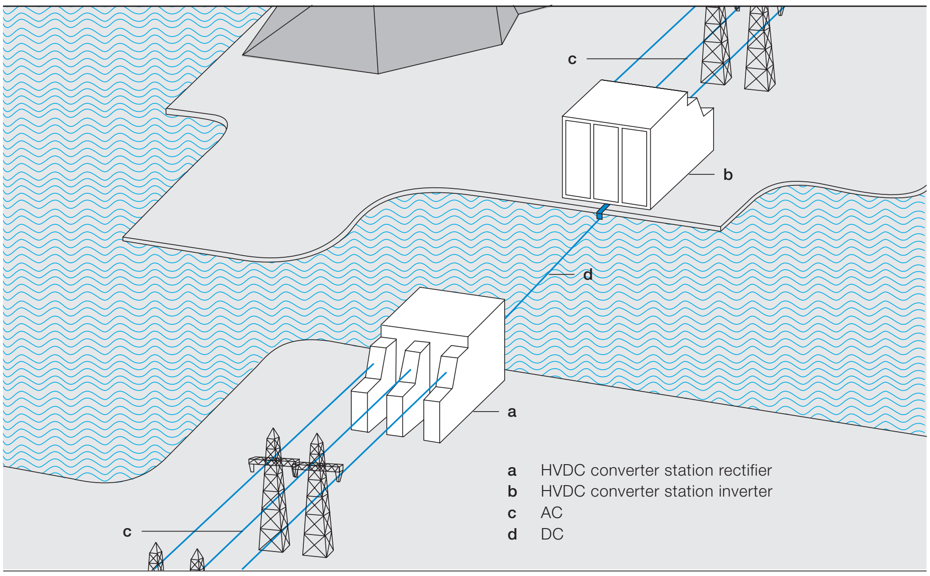
overhead lines longer than 200 km, most of the AC voltage is needed to overcome the voltage drop and phase shift due to the inductance (*L*) of the line → 1b. *C* and *L* can be compensated for using reactors/capacitors or FACTS (flexible alternating current transmission systems), or by the use of DC power.

HVDC is the most efficient method of transmitting power over substantial distances by cables → 2. HVDC has a higher initial cost – the converter stations – but because the overhead lines and cables are less expensive, there is a critical distance above which DC is more cost effective → 3. Furthermore, transmitting DC power over long distances with overhead lines is more efficient than AC transmission and is a cost-effective method of connecting two grids operating at different frequencies (asynchronous grids). This can be done via a power line between two converter stations or in a back-to-back arrangement with both converters in the same location.

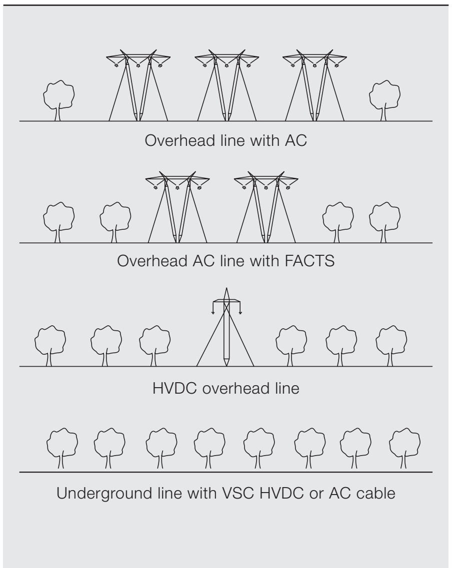
An HVDC system takes electrical power from an AC network via a transformer, converts it to DC at a converter station and transmits it to the receiving point by overhead lines or underground cables, where it is turned back into AC using another converter → 4.

The conversion is carried out using high-power semiconductor valves. Because HVDC transmits only active (real) power, no line capacity is wasted on transmitting reactive power. Therefore, the same power can be transmitted over fewer transmission lines than would be required

4 Overview of an HVDC system



5 Different transmission technologies



6 Comparison of HVDC Light and HVDC Classic

HVDC Light (power from 50 to 2,500 MW)
- Each terminal is an HVDC converter, which can support the AC network as a Statcom (SVC Light)
- Suitable for both submarine and land cable connections
- Advanced system features to enhance the performance of the AC network
- Footprint (eg, 1,200 MW): 100 x 150 x 20 m

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

using AC, so less land is needed to accommodate the lines. HVDC induces minimal magnetic fields, so the power lines may be safely built closer to human habitation ➔ 5. Upgrading an AC transmission line to carry DC can substantially increase its loadability and provide controllability that can be used to protect the power networks against blackouts.

HVDC Classic

HVDC Classic is one of two HVDC technologies used today ➔ 6. Based on thyristor power semiconductors, it is used primarily for bulk electrical transmission over long distances and for interconnecting separate power grids where conventional AC methods are not suitable. HVDC Classic transmission typically has a power rating between 100 and 8,000 MW. It uses overhead lines (for distances over 600 km) or subsea cables (for distances of 50 to 100 km), or a combination of cables and lines. Thyristor power semiconductors are line commutated, meaning that the turn-off signal is controlled by the AC line voltage reversal.

HVDC Light®

HVDC Light, introduced by ABB in 1997, is used to transmit electricity where the power involved exceeds 50 MW. It uses IGBTs (integrated-gate bipolar transistors), which, unlike thyristors, offer fully controllable power semiconductor switching. The link with the highest power rating in operation to date is the 500 MW / ±200 kV East-West interconnector between Ireland and the United Kingdom. Major advances in switching loss reduction have been accomplished – from an initial 3.7 percent to less than 1 percent – while HVDC Light technology has expanded the operating power ranges up to about 2 GW based on present voltage and current capability. HVDC Light can be used for grid interconnections, offshore links to wind farms, strengthening power networks, and powering oil and gas platforms. Thanks to the superior reactive power control capability of an HVDC Light terminal, it can increase the transfer capacity of the AC network surrounding the terminal.

ABB's HVDC Light features oil-free polymer-insulated extruded cables or mass-impregnated cables. The lighter, extruded cables, used together with prefabricated joints, enable long underground transmission. Because HVDC Light uses the IGBT as the power electronics device for the conversion, superior independent controllability can be achieved. HVDC Light offers the same benefits as traditional HVDC systems, but also provides more secure power control and quick power restoration in the event of a blackout. Because of its ability to stabilize AC voltage at the terminals, it is the ideal technology for wind parks, where the relative compactness of HVDC Light converter stations compared with HVDC Classic converter stations is a key enabler for remote offshore wind power generation.

Converter stations and transformers

Electricity generated in a power station must first be stepped up to the appropriate voltage and converted from AC to DC for long-distance transmission, and then stepped down and converted back to AC for distribution to consumers. The stepping up and down is performed by transformers. ABB is one of the world's leading suppliers of transformers and transformer components – including insulation materi-

In 2012, ABB announced a major breakthrough in the development of the DC grid – the hybrid HVDC circuit breaker.

7 HVDC cable technology

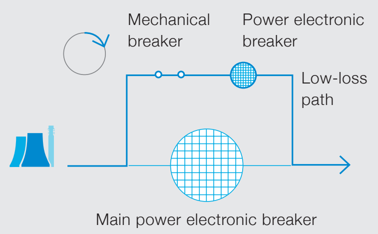
- XLPE plastic insulation
- Lightweight land cable at 10 kg/m
- Low number of joints for land installations
- Prefabricated joints
- Flexible, allowing coiling and installation from a barge (over 200 barges available)
- Flexible production (ie, AC and DC cables in the same production line)
- Maximum cable voltage of 320 kV

7a Extruded polymer HVDC cables

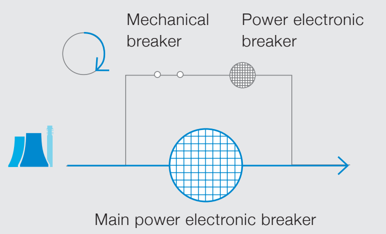
- Oil-impregnated insulation
- Heavyweight land cable at 25 kg/m
- High number of joints for land installations
- Tailored joints
- Requires special ship for installation (three such ships available globally)
- Dedicated production line for DC cables
- Maximum cable voltage of 500 kV

7b Mass-impregnated HVDC cables

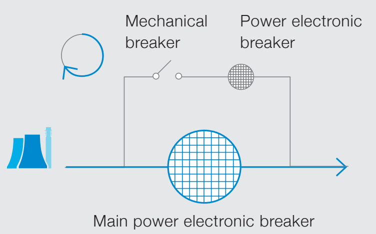
8 ABB's hybrid HVDC breaker



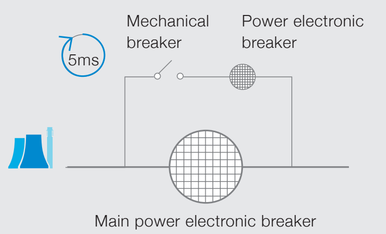
8a Normal operation: Power flow in path with least resistance (results in lower losses)



8b Power electronic breaker blocks upper current path to direct the flow into lower path



8c Mechanical breaker opens to block upper path



8d Main electronic breaker block in lower path

als and kits, tap changers, bushings and electronic control equipment – as well as service for transformers.

The core element of an HVDC system is the power converter, which serves as the interface to the AC system. The conversion from AC to DC and vice versa is carried out in a converter station using valves, which can carry current in one direction only. This feature is needed for both rectification and inversion.

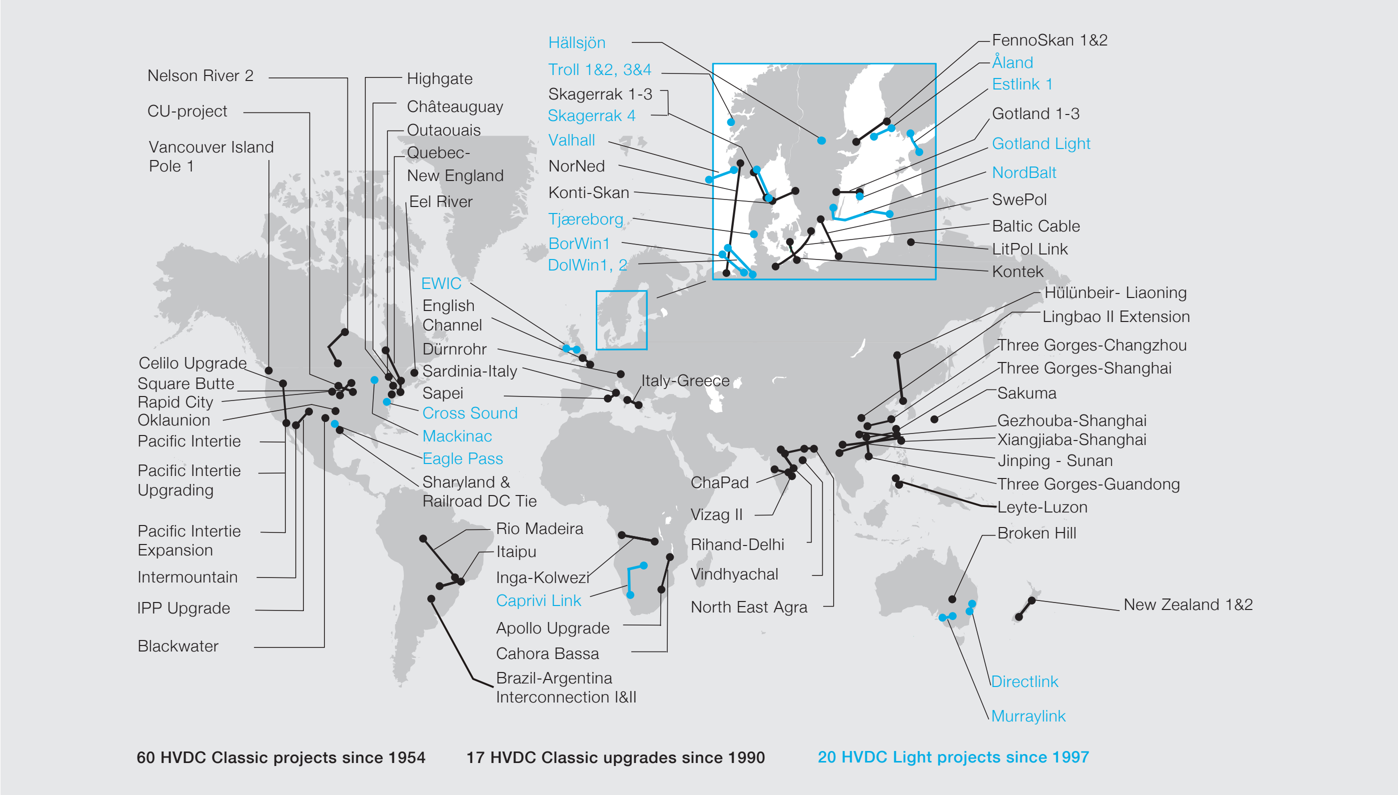
Cables

HVDC makes it possible to stretch the transmission distance for subsea or underground cables → 7, as has been shown by two world-record installations – the world's longest subsea cable, NorNed, which connects Norway to Holland via a 580 km mass-impregnated cable, and the world's longest underground cable, the Murray link, which uses two 180 km long extruded cables to connect the Riverland region in South Australia and Sunraysia region in Victoria.

Mass-impregnated submarine cables

Mass-impregnated cables have been in use since 1895. ABB has delivered more than 1,700 km of such HVDC cables all over the world. The 580 km long, 700 MW / 450 kV cable link between Norway and the Netherlands represents a milestone in both power and length for this cable type.

9 ABB has supplied more than half of the world's 170 HVDC projects.



Extruded polymer land and subsea cables (HVDC Light)

New HVDC Light cables have insulation consisting of extruded cross-linked polyethylene polymer. The insulation is triple extruded together with the conductor screen and the insulation screen.

The extruded DC cables are an important part of the HVDC Light concept. Typically, a link will have two cables, with one carrying voltage of positive polarity and the other negative. The strength and flexibility of HVDC Light cables make them suitable for submarine use as well.

Control and protection system

ABB has its own powerful, flexible and reliable control and protection system, which uses state-of-the-art computers, microcontrollers and digital signal processors connected by high-performance industrial standard buses and fiber-optic communication links. The system is called MACH (Modular Advanced Control for HVDC and SVC) and is designed specifically for converters in power applications. All critical parts of the system have inherent parallel redundancy and use the same switchover principles that have been used by ABB for HVDC applications since the 1980s.

Service and upgrades

As the installed base of HVDC links grows older, the number of upgrades to the system components increases. After about 20 years of operation it is common to upgrade valves and control systems. Often, after another 20 years, the whole link or station is upgraded or replaced with new HVDC solutions. To date no commercial HVDC link has been shut down, which demonstrates the reliability and long lifetime of the equipment and the market relevance of these links. Requests for service are growing, and ABB is commonly chosen as a turnkey service supplier.

The hybrid DC breaker

One of the major disadvantages of HVDC and one of the main reasons today's grid is primarily an AC grid, is the inability to to interrupt the flow of power and DC fault currents. The lack of ultra-fast DC breakers has been a huge roadblock to using HVDC beyond point-to-point links. That is, however, until very recently.

In 2012, ABB announced a major breakthrough in the development of the DC grid – the hybrid HVDC circuit breaker → 8. This breaker combines mechanical and power electronic switching that enables it to interrupt power flows of up to 1 GW – equivalent to the output of a large power station – in less than 5 ms. This innovation is paving the way for a more efficient and reliable electricity supply system.

Since the introduction of the first commercial subsea HVDC link, ABB has become – and remains – a leader in HVDC technologies, and is the world's leading supplier of HVDC projects to date → 9.

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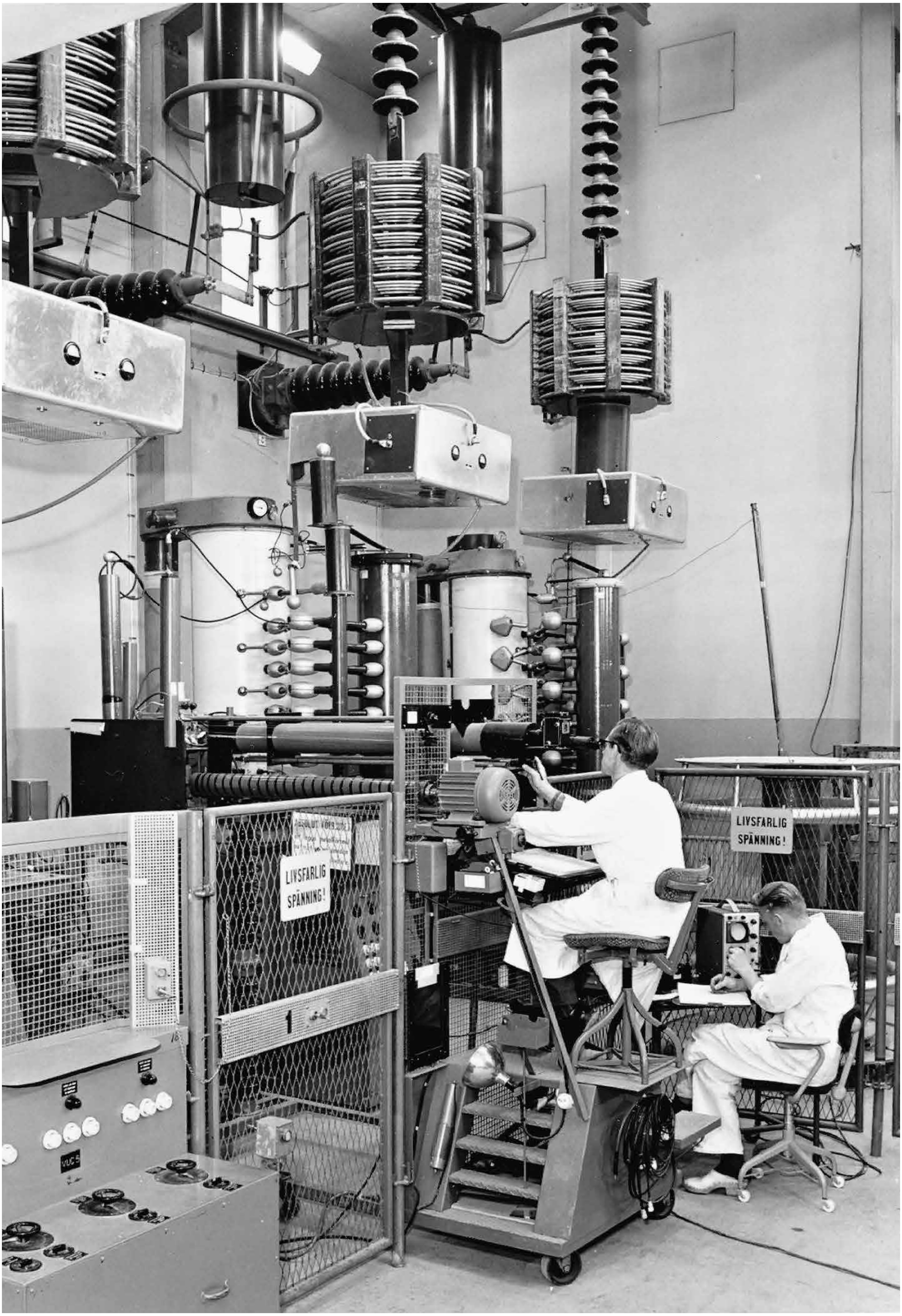
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High impact

60 years of HVDC has changed the power landscape

BO PÄÄJÄRVI, MIE-LOTTE BOHL – We are so used to the convenience of merely having to flick a switch to illuminate a room that few of us stop to think where the power that lights the lamps actually comes from. It may be generated locally, but, equally well, it may have been carried from a generator hundreds of miles away – perhaps even in a different country. The infrastructure that makes such widespread distribution of power possible is the spider's web of high-voltage direct current (HVDC) transmission lines that interlink many regions and countries in the developed world. Though having roots in the 1920s, the modern era of HVDC transmission really began in 1954 when ASEA linked the mainland of Sweden and the island of Gotland with an HVDC connector. In the intervening 60 years, HVDC technology and performance have improved at a remarkable rate – and are set to continue to do so.

Title picture
The modern era of HVDC began in 1954, but its roots extend back several decades further. Shown is a mercury-arc valve laboratory at the Trollhättan test station, which was established in 1945 and run jointly by the Swedish State Power Board and ASEA.

The developed world relies on inter-regional and international transmission lines to deliver the power that energy-hungry cities and industries consume in such vast quantities. As the world urbanizes and becomes more industrialized, and as more dispersed generators appear on the network, the demand for, and on, such power distribution infrastructure will only increase. It has long been recognized that power is more efficiently transmitted using DC than AC and early visionaries worked hard at perfecting the valves necessary for converting the high-voltage AC produced by generators into HVDC, and vice versa. This conversion is the key challenge for HVDC transmission and the HVDC story can be divided into two conversion technology eras – one dominated by mercury-arc valves and a later one in which they were supplanted by thyristor-based valves.

Mercury-arc valves

Early HVDC experiments based on mechanical, moving-contact devices were unsuccessful so pioneers soon turned their attention to the potential of mercury-arc valves. At the end of the 1920s, ASEA embarked on the development and manufacture of static converters and mercury-arc valves for voltages up to about 1 kV, and the possibility of developing valves for even higher voltages began to be investigated. In 1933, an experimental valve was produced that confirmed the validity of the principle.

Early HVDC experiments based on mechanical, moving-contact devices were unsuccessful so pioneers soon turned their attention to the potential of mercury-arc valves.

In 1944, Dr. Uno Lamm, "the father of HVDC" → 1, successfully operated a rectifier and an inverter in his laboratory in Ludvika, Sweden at a power rating of 2 MW and voltage of 60 kV. The time was now ripe for service trials at powers higher than

The 20 MW / 200 A / 100 kV Gotland link marked the beginning of the modern era of HVDC and the concept was so successful that it has remained basically unchanged since.

those that could be accommodated at Ludvika so a test station, run jointly by the Swedish State Power Board and ASEA, was established in 1945 at Trollhättan and a 50 km power line was made available for service trials ➔ title picture.

Further technical development of the mercury-arc valve – as well as other components in the converter stations and transmission equipment such as transformers, reactors, switchgear, and protection and control equipment – resulted in a completely new approach that was implemented by ASEA in the 1954 HVDC link to the island of Gotland ➔ 2. This 20 MW / 200 A / 100 kV line marked the beginning of the modern era of HVDC and the concept was so successful that it has remained basically unchanged since.

ASEA's second order for HVDC transmission equipment – for a 160 MW / ± 100 kV Anglo-French cross-channel link – followed soon after and the stage was set for the development of converters that could handle twice the voltage and would have 10 to 20 times higher power than would be required by subsequent installations.

Following the English Channel project, several further HVDC links using mercury-arc valves were built during the 1960s: Konti-Skan (250 MW) between Sweden and Denmark; Sakuma (300 MW) in Japan; the inter-island connection in New Zealand (600 MW); and the Italy – Sardinia (200 MW) link. The largest mercury-arc valve transmission built by ASEA was the Pacific HVDC Intertie in the United States, a 1,440 MW (later re-rated to 1,600 MW) / ± 400 kV transmission from The Dalles, Oregon to Los Angeles, California ➔ 3. In fact, this was the last mercury-arc valve project commissioned as the second technology era – that of thyristors – was about to dawn.

1 Dr. Uno Lamm, "the father of HVDC"

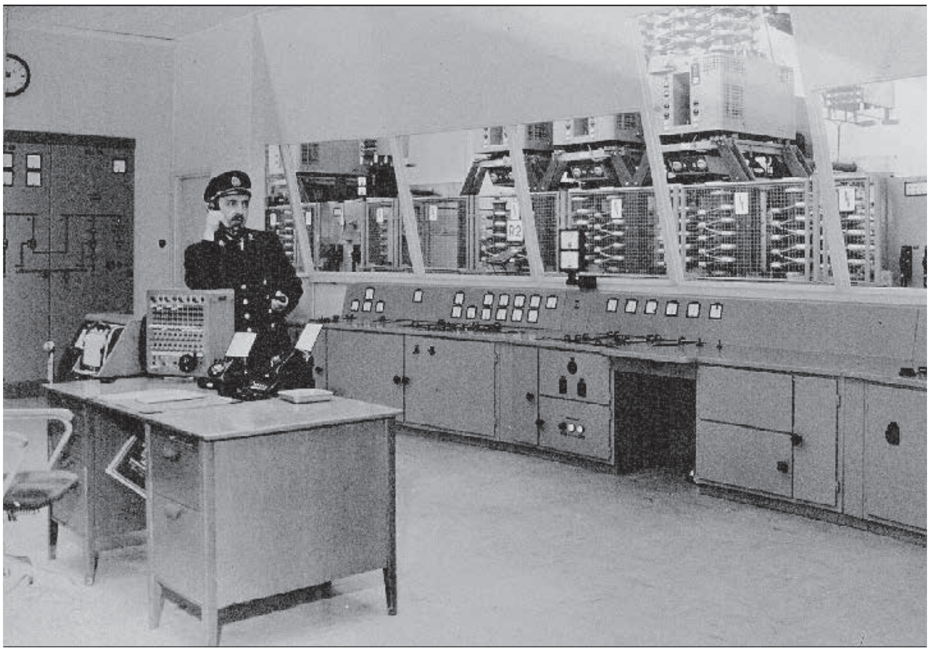
Thyristor-based converters

Mercury-arc-valve-based HVDC had come a long way in a short time, but was a technology that still harbored some weaknesses. One of these was the difficulty in predicting the behavior of the valves themselves – for example, because they could not always sustain the reverse voltage, they suffered from arc-backs. Also, mercury-arc valves require regular maintenance, during which absolute cleanliness is critical. A valve that avoided these drawbacks was needed.

The invention of the thyristor in 1957 had presented industry with a host of new opportunities and HVDC transmission was seen as one promising area of application for these new devices.

The invention of the thyristor in 1957 had presented industry with a host of new opportunities and HVDC transmission was seen as one promising area of application for these new devices. All through the first half of the 1960s, work continued on the development of high-voltage thyristor valves as an alternative to the mercury-arc type. In the spring of 1967, one of the mercury-arc valves used in the Gotland HVDC link was replaced with a thyristor valve ➔ 4. It was the first time anywhere that this kind of valve had been put into commercial

2 Gotland control room in the 1950s



3 Pacific Intertie mercury-arc valve in Sylmar, Los Angeles

4 Mercury-arc valves and thyristor valves installed at Gotland 1

The largest mercury-arc valve transmission built by ASEA was the Pacific HVDC Intertie – 1,440 MW, later re-rated to 1,600 MW.

operation for HVDC transmission. Thyristor technology had ushered in a new era of HVDC and rendered the mercury-arc-based approach obsolete. After a trial of just one year, the Swedish State Power Board ordered a complete thyristor valve group for each Gotland link converter station and increased the transmission capacity by 50 percent at the same time. In parallel, tests were carried out on the Gotland submarine cable, which had been operating without any problems at 100 kV, to see if its voltage could be increased to 150 kV – the level needed to transmit the higher power. The tests showed that it could and this cable was subsequently operated at an electrical stress of 28 kV/mm, which is still the worldwide benchmark for large HVDC cable projects.

The new valve groups were connected in series with the two existing Gotland mercury arc valve groups, thereby increasing the transmission voltage from 100 to 150 kV. This higher-rated system – the new rating being another world first for the Gotland transmission link – was brought into service in the spring of 1970.

With thyristor valves, convertor stations became much simpler, cheaper and more reliable and semiconductors have been used in all subsequent HVDC links.

Other companies now entered the field: Brown Boveri (BBC), which later merged with ASEA to form ABB, teamed up with Siemens and AEG in the mid-1970s to build the 1,930 MW / ±533 kV Cahora Bassa HVDC link between Mozambique and South Africa → 5. The converter valves for this transmission were oil-immersed. The same group then went on to build the 2,000 MW / ±500 kV Nelson River 2 link in

5 Oil-insulated and oil-cooled thyristor outdoor valves in the Cahora Bassa HVDC link between Mozambique and South Africa

6 600 kV valve test for Itaipu

Canada. This was the first project to employ water-cooled HVDC valves.

The mid-1970s saw the completion of further projects: The Skagerrak link between Norway and Denmark, Inga-Shaba in the Congo, and the CU Project in the United States. The converter valves in these projects were air-cooled. The Pacific Intertie was also extended twice in the 1980s, each time with thyristor converters, to raise its capacity to 3,100 MW at ± 500 kV.

In 1983, Gotland was revisited with a new 130 MW / 150 kV cable being laid – Gotland 2. Gotland 1 and Gotland 2 operated independently, but Gotland 3, an additional link laid in 1985 to satisfy increasing demand and allay supply safety fears, usually works with Gotland 2 to form a bipolar link (though it too can operate independently). In bipolar transmission, a pair of conductors is used, each at a potential with respect to ground, with opposite polarity. Since these conductors must be insulated for the full voltage, transmission line cost is higher than a monopole with a return conductor, but this is more than compensated for by its advantages, such as negligible earth-current flow, lower absolute current rating (each line carries only half the current for the same power), fault tolerance and so on. Gotland 2 and 3, with a total rating of 2 × 130 MW / ± 150 kV featured new water-cooled converters. This bipolar link has provided extremely good availability with no interruption of power transmission in 10 years.

In 1967, one of the mercury-arc valves used in the Gotland HVDC link was replaced with a thyristor valve – the first commercial use in HVDC transmission.

Itaipu

The contract for the Itaipu HVDC link in Brazil was awarded to the ASEA-PROMON consortium in 1979. The sheer scale and technical complexity of the Itaipu project presented a considerable challenge, and it can be seen as the start of a new chapter in the HVDC story. The power rating was the highest ever seen in HVDC – two bipoles at 6,300 MW / ± 600 kV → 6. The project was completed and put into operation in several stages between 1984 and 1987 → 7. It played a key role in the Brazilian national power infrastructure, supplying a large

7 12,600 MW power station at Itaipu

The Itaipu power rating was the highest ever seen in HVDC – two bipoles at 6,300 MW / ± 600 kV.

portion of the electricity for the city of São Paulo. The experience gained in the course of the completion of the Itaipu HVDC project has paved the way for all later HVDC high-power transmissions.

Some milestones here are:
- The 2,000 MW / ± 500 kV Québec to New England link. This was among the first large multiterminal HVDC transmission systems to be built anywhere.
- The 1,920 MW / ± 500 kV Intermountain Power Project in the United States. The high earthquake-proofing requirements were met by suspended valve structures – used here for the first time and the standard solution since.
- The 6,400 MW / ± 800 kV Xiangjiaba-Shanghai transmission link. This record-breaking link uses UHVDC (ultrahigh-voltage direct current) – the technology used in the longest and most powerful transmission links. The introduction of the 150 mm, 8.5 kV PCT (phase control thyristor) was a major factor in enabling performance improvements in this technology, the next generation of UHVDC.

HVDC – key for a sustainable grid based on renewables

HVDC is now the method of choice for subsea electrical transmission and the interconnection of asynchronous AC grids – providing efficient, stable transmission and control capability. HVDC is also the technology of choice for long-distance bulk power transmission and is able to send vast amounts of electricity over very long distances with low electrical losses. But HVDC technology is constantly challenged to achieve higher ratings for voltage and current, conquer even longer distances with overhead lines, cables or a combination of these, and to further reduce transmission losses.

ABB's 1992 vision to create a DC grid that solves the problem of renewable energy generators often being situated far from the users they serve is now close to being realized by the multiterminal HVDC links being built on land and offshore. HVDC has become an established technology and an integrated part of AC grids, as well as the key for a future sustainable grid based on renewables.

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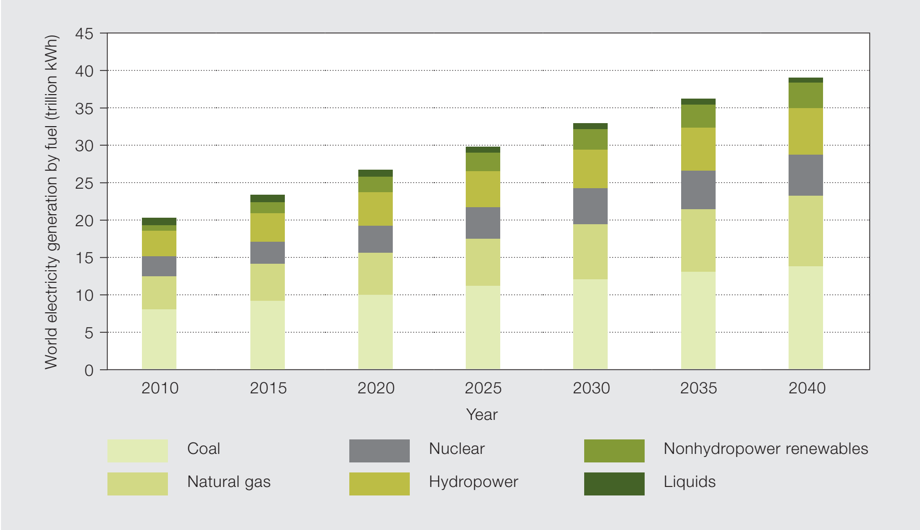
Corridors of power

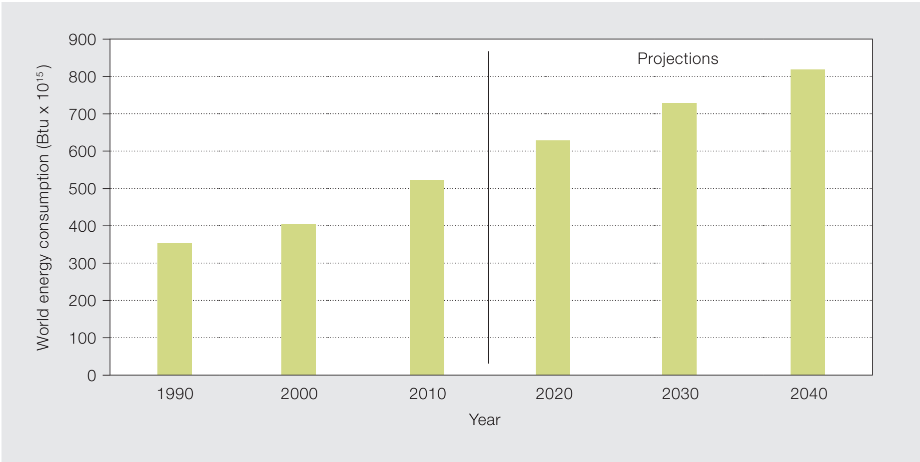
Next-generation UHVDC will send more power through existing transmission corridors

RAUL MONTANO, BJORN JACOBSON, DONG WU, LILIANA AREVALO – With a forecasted average annual growth rate of 9 percent [1], the world's voracious hunger for clean, reliable electrical power is set to continue for many years to come. Power utilities struggle to keep up with this surging demand. Indeed, in order to cope, they would need to increase their power generation base by an average of 11 percent each and every year for the foreseeable future [1]. A further complication arises in that much power generation capacity is situated at some distance from those places where it is consumed – a trend exacerbated by increasing urbanization and industrialization. To ensure future supply, power transportation corridors will have to increase their voltage- and current-carrying capabilities. Despite the maturity of ultrahigh-voltage direct current (UHVDC) technology, these new ratings represent major technological steps that will have to be taken in a very short time.

1 World energy forecast from EIA [1]



1a World electricity generation by fuel (2007-2035) in trillion kilowatt-hours



1b World market energy consumption (1990-2035) in quadrillion (10^{15}) Btu

World energy consumption and the power generation to match it are set to continue to rise for the foreseeable future [1] ➔ 1. Unfortunately, the bulk of the energy resources needed to satisfy rising demand are not located near the load centers. For example, in China, large resources of untapped hydroelectric power – up to 500 GW – are available in the west of the country, in Sichuan, Xizang and Yunnan provinces. In addition, additional significant coal-fired generation capacity is planned in the Xinjiang area. The distance of these generation sources from the heavily industrialized regions along the coast in eastern China (Beijing, Shanghai) and southern (Guangzhou) China is between 1,000 and 3,000 km.

All over the world, diverse factors make the construction of new transmission lines ever more complex: public resistance, narrow transmission corridors, limited availability of rights of way, requirements to minimize routes through forests and other sensitive ecosystems, and the general protection of flora, fauna and people. If a transmission corridor is long, the chance of exposure to one or more of these factors is increased.

> The bulk of the energy resources needed to satisfy rising demand are not located near the load centers.

Often, the best solution is to increase the power-carrying capacity of existing routes.

China, for example, is investigating the possibility of using a voltage rating of 1,100 kV for power transmissions of 10 to 13 GW per line for distances over 2,000 km in order to achieve as much power throughput per line as possible. For shorter distances, the utility in China has been considering an increase of the rated current of 800 kV DC systems. Despite the maturity of HVDC technology, these new ratings – of voltage or current – represent major technological steps that will have to be taken in a very short time.

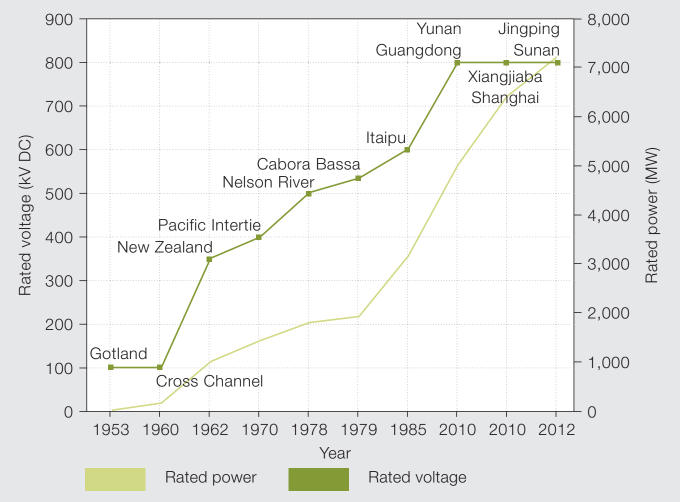
Technical-economical solution

In recent years, 800 kV DC transmission systems, capable of transmitting more than 7 GW over 1,400 km, have been in operation ➔ 2. However, when the transmitted power is increased above 10 GW, 800 kV systems become much less economic because it is not possible to transmit these power levels over a single UHVDC transmission line – two lines are needed.

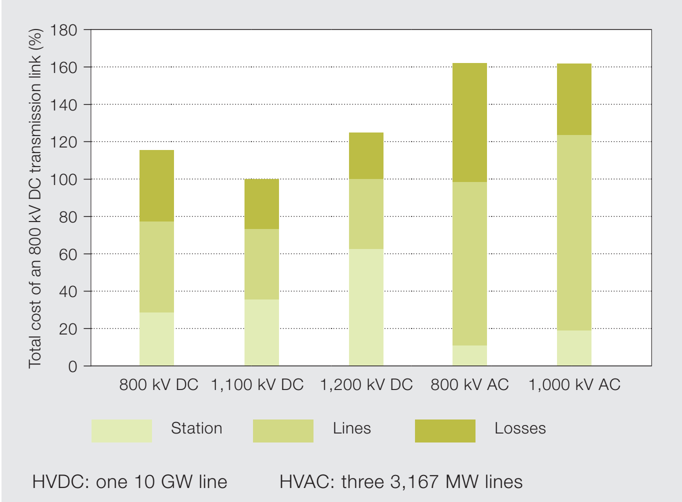
Title picture

Rising demand and the difficulty of building new HVDC transmission lines means new technology has to be developed to allow existing lines to carry more electrical power from distant generators to centers of consumption. Shown is the valve hall in the Xiangjiaba-Shanghai Fengxian UHVDC station.

2 HVDC systems evolution



3 Cost comparison of various options in percentage of the total cost of an 800 kV DC transmission link



There is no question that using higher voltages reduces losses and allows target energy costs to be achieved → 3. However, for power lines to be able to cope with the higher-voltage demands that will soon be put upon them, new system components, especially thyristor valves, will have to be developed.

Challenges

ABB has worked for many years in high-voltage power transmission and this experience is exploited in the development of products that meet the challenges faced when transporting power over very long distances at very high voltages. Several aspects become critical when designing UHVDC systems: availability and reliability, electromechanical design and equipment transport, and the type of DC yard.

Availability and reliability

UHVDC systems designed to transmit power levels above 10 GW need to cope with higher requirements on availability and reliability. After all, one single-pole trip will disconnect energy equivalent to half of the installed capacity of a very large hydroelectric power plant – eg, the 12 GW Itaipu plant in Brazil. This will also impose a high strength requirement on the AC systems at both ends of the UHVDC transmission. Also, thorough investigations are necessary to ensure that single, small events that occur in regions into which multiple UHVDC systems feed do not escalate into something more dramatic. This all means that reliability is a very important issue and represents a major design parameter.

Electromechanical design and equipment transport

Outdoor high-voltage insulators face many challenges, among which is the risk of flashover – atmospheric pollution, for example, can lead to excessive contamination of the insulator and thus to flashover if creepage length and general design is not adequate. Insulators designed for higher voltages have to be longer – necessitating a diameter increase to provide the required mechanical stability and this, in turn, decreases flashover performance. The battle to reconcile insulation, mechanical and electrical requirements can quickly spiral into a runaway situation if great care is not taken in the design phase [2].

The equipment subjected to the new, higher voltages will be larger, which brings further challenges. For example, converter transformers are assembled, tested and shipped to site. Shipment might be no longer possible with larger-sized transformers, so on-site manufacturing and the reliability issues this entails have been assessed.

Reliability throughout the entire range of products and components destined for use in these new, higher-voltage environments is of critical importance – electrode size, corona shielding, terminal forces, etc. all need to be properly designed and tested to guarantee a cost-effective solution with the reliability that the new generation of UHVDC systems requires → 4.

> All over the world, diverse factors conspire to make the construction of new transmission lines ever more complex.

Indoor vs. outdoor DC yard

Today, both outdoor and indoor DC yards have been adopted by different 800 kV UHVDC projects. However, operational experience at this voltage level is still limited [2]. One reason for selecting an indoor solution is to minimize the footprint of the converter station → 5. For equipment inside this weather-protected building, the creepage distance needed and the mechanical strength required can be reduced. Switching impulse voltage will be the dimensioning parameter. Therefore, smooth electrodes with a larger diameter can be adopted to reduce the required air clearance [2].

The cost of the building makes the indoor approach more expensive than the outdoor. In addition, depending on the requirements on the ambient conditions inside the hall, auxiliary equipment, such as a humidity controller, may be required [2]. However, part of the building costs will be returned by the reduced cost of the apparatus itself and the costs saved by reducing outages will usually more than cover the rest. A reduced risk of failure is the major benefit of the indoor solution.

4 High-voltage test laboratory

5 Indoor DC yard

ABB technology development

In 2010, ABB started research into and development of the key components for the next generation of UHVDC transmission systems, ie, those exposed to the new rated voltage (1,100 kV DC). By means of advanced electromagnetic simulations, transient studies and high-voltage testing, ABB has developed prototypes for the converter valve, valve hall design, converter transformer, bypass switch, radio interference capacitor, surge arrester, transformer bushing and wall bushing. Also, conceptual designs for station layout and indoor DC yards have been completed.

China is investigating using 1,100 kV for power transmissions of 10 to 13 GW per line for distances over 2,000 km.

New UHVDC applications

The Chinese economy has exhibited an average annual growth rate of around 12 percent over the last 30 years. Improvement in affluence and economic growth is closely associated with increased energy requirements. To cope with the increasing electricity demands, and to keep the costs reasonable, China has pioneered the implementation of new high-voltage systems in both the AC and DC realms. It was the first country to commission and fully operate 800 kV DC transmission systems and more than 21,000 GW of transmission capacity is now installed at this rated voltage. Further economic growth is expected in the coming years – and with it further demand for high-voltage transmission systems.

After 2020, a further seven hydroelectric power projects, with a total rating of 110 GW, are planned in Xizang. The power from these will be transmitted to the eastern and southern provinces of China. To enable the bulk transmission from these and from other projects, even further development of UHVDC systems will be required – either at 1,100 kV DC or at existing voltage ratings with higher current-carrying capabilities. Presently, there is no immediate market interest for the new UHVDC transmission systems outside of China. However, this may change with the emergence of future hydroelectric and solar generation sources in Africa, India, the United States and South America that are far removed from the centers of consumption and that are needed to satisfy the world's apparently insatiable hunger for power.

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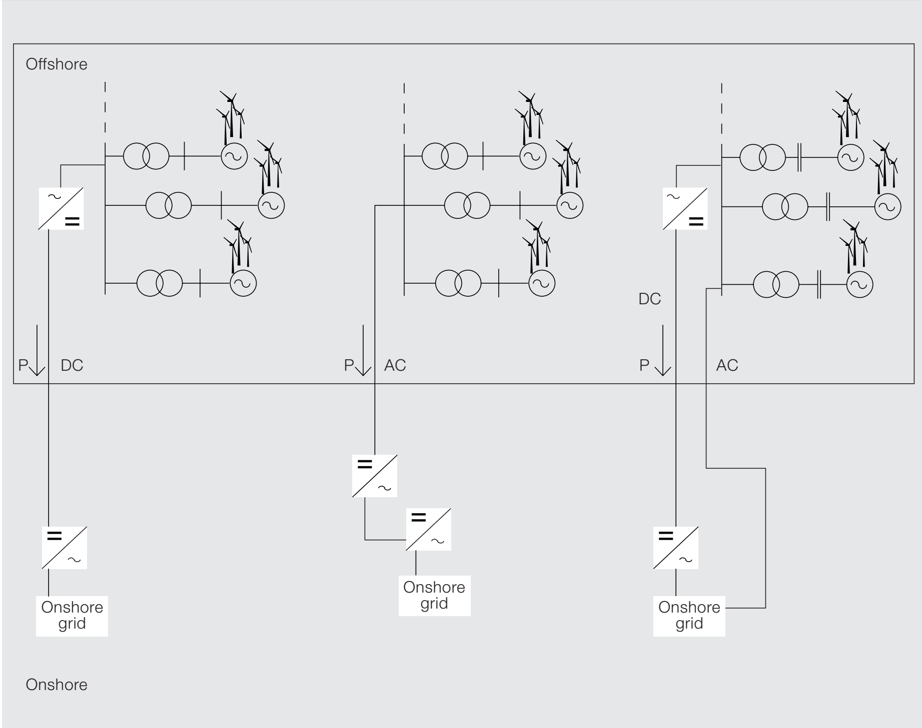
Strong winds, high yield

HVDC Light® technology goes farther out to sea

PETER SANDEBERG – Under pressure to decrease the environmental impact of generating electrical power, coupled with continuously increasing demand, energy producers must utilize more of the earth's natural resources to harvest additional power. While many parts of the world bask in glorious sunshine, northern Europe tends to experience winds that can wreak havoc. On the flip side, the construction of onshore and offshore wind power plants have successfully exploited these winds to produce clean energy. Given that the higher average offshore wind speeds can result in an energy yield of up to 70 percent higher than that generated on land, it is no wonder that the next 15 years will see an increase in the number of offshore plants. However, the farther out to sea, the greater the challenge of ensuring the transmission of a stable energy supply to the mainland. This challenge is being met with ABB's HVDC Light technology.

1 Alternative HVDC and HVDC/HVAC connection schemes



1a Direct connection solution

1b Back-to-back solution

1c Parallel solution combines HVAC and HVDC

The United Nation's Intergovernmental Panel on Climate Change (IPCC) has predicted that clean energy will have to at least treble in output in order to avoid catastrophic climate change [1, 2]. Over the past few decades, wind power generation has been making a vital contribution to the global effort of lowering the environmental impact of electrical power generation. Championed as an increasingly important source of renewable energy, its contribution is set to increase over the next 15 years with the construction of large offshore wind parks in Northern Europe with a planned capacity of up to 40 GW of power. One of the main attractions of going offshore is the frequency of very strong winds, which in turn can yield up to 70 percent more energy than onshore wind parks. Even though it is costlier to construct offshore wind power parks, this increase in yield combined with the fact that many renewable energy technologies have substantially advanced in terms of performance and cost, could offset these costs in the long run.

As well as growing in terms of rated power, offshore wind power plants are being located farther from the coasts and the grid entry points. The impact of large-scale offshore wind power penetration may potentially affect the stability of the mainland grid, particularly considering the intermittent nature of wind. The tendency toward long distances in combination with often weak coastal connections mean that tough technical challenges need to be overcome:

- The power level of the connected park
- The distance to the connection point
- The type of transmission
- The AC network strength at the connection point
- The fault ride-through capability in case of AC grid faults
- The start-up of the wind power park
- The environmental impact of the transmission system

Average offshore wind speeds can result in an energy yield of up to 70 percent higher than that generated on land.

In addressing each of these challenges, ABB has, using its HVDC Light transmission technology, developed a detailed design for offshore HVDC (high-voltage direct current) systems that can safely and reliably integrate large-scale wind-power production.

To begin with, given that each wind power plant will typically be in range of a few hundred MW up to several GW, HVDC is capable of transmitting power levels of between 100 MW and 1,200 MW with only one cable circuit. It is considered an economically viable solution especially in situations where the distance to the connecting AC grid exceeds 70 to 120 km.

Closer to shore, a wind power park could be connected with either AC or DC transmission or a combination of these systems. It offers support to meet onerous grid access requirements and helps to improve power quality issues at the connection point. Its technology provides superior control and quick power restoration during and after disturbances and contingencies including blackouts. And it supports weak grids with black-start capability, fine-tuning of AC voltage and reactive power and the ability to energize wind power parks at zero or low wind conditions. Last but not least, this transmission system is ideal for stabilizing irregular electricity flows by quickly compensating for power fluctuations.

Offshore wind power plants are growing in terms of rated power and are being located farther from the coasts and the grid entry points.

2 Offshore wind projects connected by HVDC Light

Project	Company / location	Rated power (MW)	System voltage (kV)	DC cable length (km)	Year of completion
BorWin1	TenneT (Germany)	400	DC: ±150 AC: 155/400	SM*: 2x125 UG*: 2x75	2009
DolWin1	TenneT (Germany)	800	DC: ±320 AC: 155/400	SM*: 2x75 UG*: 2x90	2014
DolWin2	TenneT (Germany)	900	DC: ±320 AC: 155/380	SM*: 2x45 UG*: 2x90	2015

*SM = Submarine; UG = Underground

Capturing offshore wind with HVDC solutions

A variety of different transmission schemes are possible using HVDC technology alone and in combination with HVAC ➔ 1.

The direct connection solution shown in ➔ 1a and the back-to-back solution illustrated in ➔ 1b can use a frequency in the wind power park that is not synchronized with the onshore grid. The wind power park is also isolated from electrical disturbances in the onshore grid, meaning that significant "fault ride-through" capability is achieved.

The parallel case demonstrated in ➔ 1c shows how HVAC and HVDC can be combined and is an example of a stepwise expansion approach that enables transmission capacity to be added in stages. The advantages of such a scheme include higher energy availability, the potential to include changes and incorporate new technology as the wind power park develops and, from a business point of view, incremental investments.

At startup, an HVDC Light converter station provides fast and efficient voltage control as the offshore grid is being energized. The voltage is ramped up smoothly at a rated frequency (to prevent transient overvoltages and inrush currents) after which the wind turbine generators are safely connected to the offshore grid. The onshore (receiving) converter station is located either near the shore or farther inland. Even though the grid is often weak along the coastline, HVDC Light technology is designed to enhance the system by providing voltage stability support. Moreover, this technology will literally make the offshore grid, including the connected wind turbines, electrically immune against transient disturbances originating from the onshore grid. For example, during onshore AC network faults the onshore converter station can bypass the surplus energy from the wind power plant into a braking resistor. Once the network fault is cleared the resistor is disconnected and normal power flow is re-established. This practice protects the wind turbines and other equipment from stresses which, in the long term, helps extend their life cycle.

From an environmental point of view, HVDC Light transmission systems provide many benefits, including:

- An underground, oil-free extruded cable system from the shore to the AC connection point
- Twin cable installation, which in turn neutralizes magnetic fields
- An enclosed converter station to efficiently suppress noise
- A smaller station footprint

Offshore platforms with dual functionality

The trend nowadays is toward large offshore power plants located remotely in a harsh and unforgiving environment that can accommodate both HVDC converters, as well as operations and maintenance personnel. The first two platforms built for offshore wind HVDC converter stations were based on a conventional topside jacket solution. In close cooperation with a Norwegian yard, ABB developed a flexible, highly innovative, robust and scalable platform for greater production efficiency and ease of installation (no heavy-lift vessels or jack-up operations are required). This platform is based on a combination of semisubmersible and gravity-based designs – ie, it acts as a semisubmersible platform

3 Dörpen West onshore station for the DolWin1 wind farm

3a Back view

3b Side view

4 The DolWin2 offshore platform for the North Sea

during transport and installation, after which it is ballasted down to sit solidly on the seabed.

HVDC in action

The increasing number of wind power parks combined with the growing distance between offshore power generation and onshore consumption are two of the main driving factors for the adoption of HVDC Light. In fact, HVDC has been and will be used in some major European projects, all of them in the North Sea ➔ 2.

BorWin1

In 2007 ABB received an order from E.ON-Netz (now TenneT) to integrate one of the largest and most remote offshore wind power parks into the German grid by means of a 400 MW HVDC Light system. The project order, known as BorWin, is the world's first offshore wind HVDC connection. Full grid code compliance ensures a robust network connection of the wind power plant, which consists of 80 wind generators rated at 5 MW each; offshore and onshore converter stations; and 75 km of underground and 125 km of submarine cables. The wind energy feeds into a converter substation at Diele, near Papenburg, on the German mainland where the power is injected into the 400 kV grid. This project reduces CO_2 emissions by nearly 1.5 million t per year.

DolWin1

Another example of this type of solution is the 800 MW DolWin1 HVDC Light connection, which will bring power to the grid connection point at Dörpen West in Germany, about 90 km inland ➔ 3. ABB is responsible for system engineering, including design, supply and installation of the offshore converter station, including the platform, 75 km of DC submarine cables, 90 km of underground cables and the onshore converter station. Scheduled to be operational in 2014, this network of offshore wind power parks is expected to reduce CO_2 emissions by 3 million t per year.

DolWin2

For the DolWin2 project, the wind power parks will be connected to an HVDC converter station installed on an offshore platform in the North Sea ➔ 4. The generated power will be transmitted through a 45 km long DC submarine cable and a 90 km long underground cable to the HVDC onshore station at the grid connection point of Dörpen West.

The transmission system will have a total capacity of 900 MW at ± 320 kV, which will make it the world's largest offshore HVDC system. This HVDC Light connection provides numerous environmental benefits, such as electrical losses of less than 1 percent per converter station and neutral electromagnetic fields. Compact converter stations will help reduce carbon dioxide emissions by more than 3 million t per year by replacing fossil-fuel-based generation.

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From far away

Efficient and cost-effective long-distance power transmission with HVDC

ABHAY KUMAR, ALF PERSSON – As the energy needs of the world increase, the demand for long-distance energy transmission also rises. Areas needing electrical energy are often located far away from the source of energy, be it water, solar or wind. ABB's HVDC Classic technology serves as a cost-effective alternative to AC transmission for long-distance and bulk-power transmission as well as for interconnecting asynchronous AC networks. For connecting remote and large-scale generation to load centers HVDC is an attractive solution with extremely low transmission system losses. ABB continues to create HVDC solutions to suit the many scenarios encountered in the transmission world.

HVDC technology uses thyristors for conversion and typically has a power rating of several hundreds of megawatts, though many are in the 1,000 to 3,000 MW range, and some even as high as 8,000 MW. HVDC is suitable for overhead lines as well as undersea/underground cables, or a combination of cables and lines. It can also be configured as back-to-back HVDC stations. This configuration enables two asynchronous grids to exchange power and ensures that in the event of a disturbance in one, the other supports it.

The interconnection through HVDC does not add to the short-circuit capacity of the networks. This allows for less-frequent replacement of the heavy-duty switchgear equipment, keeps grids immune from disturbances and minimizes affected areas. By controlling its power flow, an HVDC system stabilizes the grid in the interconnected networks and increases the security of supply. As HVDC systems cannot be overloaded, uncontrolled cascade tripping of lines is avoided. For example, during the massive 2003 blackout that affected the entire northeastern United States, the HVDC connections shielded the Quebec system in Canada from frequency swings.[1]

HVDC lines use the right of way (m/MW) very effectively and can also be operated at reduced voltage in case some section of a line has issues with insulation withstand capability. HVDC technology enables long underwater transmission links with low losses. Traditional AC transmission systems with underwater cables cannot be longer than about 60 to 100 km as it would require massive reactive compensation en-route.

The configuration enables two asynchronous grids to exchange power and ensures that in the event of a disturbance in one, the other supports it.

Footnote

1 http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/BlackoutFinal-Web.pdf

1 The NorNed station

2 A selection of ABB's HVDC commissions

- The Itaipu project in Brazil supplies 50 Hz power into a 60 Hz system and economically transmits large amounts of hydropower (6,300 MW) over long distances (800 km).
- The Leyte-Luzon project in the Philippines supplies bulk geothermal power across an island interconnection and improves stability to the Manila AC network.
- The Rihand-Delhi project in India transmits bulk thermal power (1,500 MW) to Delhi, ensures minimum losses, least amount of right-of-way, and better stability and control.
- The Garabi project in Argentina is an independent transmission project transferring power from Argentina to Brazil. The back-to-back HVDC system ensures a supply of 50 Hz bulk power (1,100 MW) to a 60 Hz system under a 20-year power supply.

Sustainability showcase: NorNed

The 580 km NorNed HVDC monopolar transmission link with a 700 MW / ± 450 kV transmission capacity, is the longest underwater high-voltage cable in the world → 1. Commissioned in 2008, the converter stations are located at the Feda substation in Norway and at the Eemshaven substation in the Netherlands – a span of 580 km. The interconnection is jointly owned by the two state power grid companies, TenneT in the Netherlands and Statnett in Norway. The interconnection, which is based on market coupling, has led to power trading between the two countries and increased the reliability of electricity supply in both.

To optimize cable costs and cable losses, NorNed has two fully insulated DC cables at ± 450 kV although it is a monopolar link. This makes the DC current small and creates low cable losses, but requires a higher converter voltage and has a record voltage of 900 kV for a 12-pulse converter.

Scandinavia has a largely hydro-based production system whereas the Netherlands and surrounding countries have a system based largely on fossil fuels. Hydropower is easily regulated and stored in existing dams. This allows the Dutch grid to be optimized by using hydropower to cover peak loads during the day. At night, power can be transported back to Scandinavia, thereby saving electric energy in the dams. The result is a more stable output from the fossil-fuel-fired plants, thus minimizing emissions. Additionally, the stabilized grid allows integration of new renewable generation in the form of wind power.

The security of supply has improved since production resources in a larger area are available as a backup in the event of network disturbances. The electricity market has benefitted as the link has enabled electricity trading between two distant, isolated markets.

The link demonstrates that HVDC technology offers the unique capability to build long underwater or underground cable transmission lines with low losses. The NorNed link has losses of only about 4 percent.

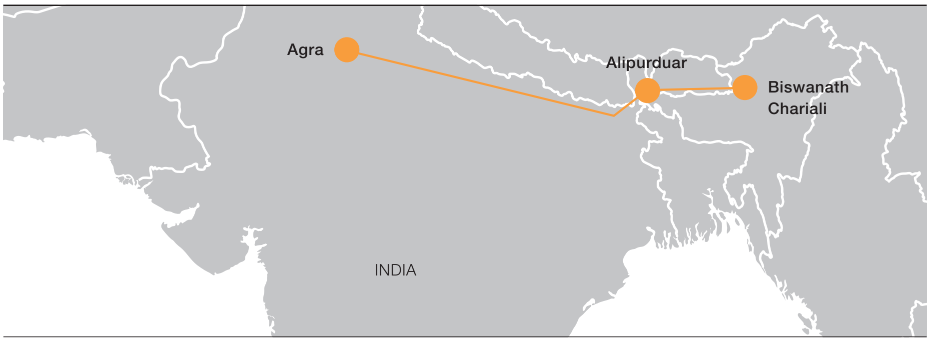
North-East Agra

ABB has built HVDC transmission projects all around the world → 2. A unique project is currently under construction in India. When commissioned in 2016, the North-East Agra HVDC link, officially known as ± 800 kV / 6,000 MW HVDC Multi Terminal NER/ER-NR/WR Interconnector-I, will

The interconnection, which is based on market coupling, has led to power trading between the two countries and increased the reliability of electricity supply in both.

ABB's HVDC transmission system was chosen in large part because of the advantage of the technology needing only a minimum right of way.

3 The North-East Agra HVDC link will cover a distance of 1,728 km.



be the first multiterminal HVDC project at 800 kV. The link comprises four terminals in three converter stations with a 33 percent continuous overload rating, enabling an 8,000 MW conversion. It will be the largest HVDC transmission system ever built, having the highest converter capacity at 8,000 MW and the first one having 800 kV indoor DC halls.

Power Grid Corporation is constructing this HVDC link to transmit clean hydroelectric power from India's northeast region to Agra, the city of the Taj Mahal, over a distance of 1,728 km → 3.

The solution also acts as a firewall, isolating disturbances and preventing them from spreading from one network to the other.

One converter station (Biswanath Chariali) will be in the state of Assam, and a second (Alipurduar) in the state of West Bengal in eastern India. The other end of the DC line will terminate at Agra, where two bipolar converters will be connected in parallel. The 800 kV equipment yard at Agra will be indoors.

Northeast India has abundant untapped hydropower resources of the order of 50 to 60 GW scattered over a large area, but load centers are hundreds or even thousands of kilometers away. Transmission lines must pass through a very narrow patch of land (22 km × 18 km) in the state of West Bengal, which has borders with Nepal and Bangladesh. ABB's HVDC transmission system was chosen in large part because of the advantage of the technology needing only a minimum right of way.

The system will have two ± 800 kV converter poles in Biswanath Chariali and two ± 800 kV converter poles in Alipurduar, whereas Agra will have four ± 800 kV converter poles. As each converter pole has a nominal rating of 1,500 MW with a continuous overload rating of 2,000 MW, it is possible to compensate for the loss of any converter pole. If for instance Pole 1 in Agra is lost, Poles 2, 3 and 4 can still supply the rated 6,000 MW to the Agra region → 4.

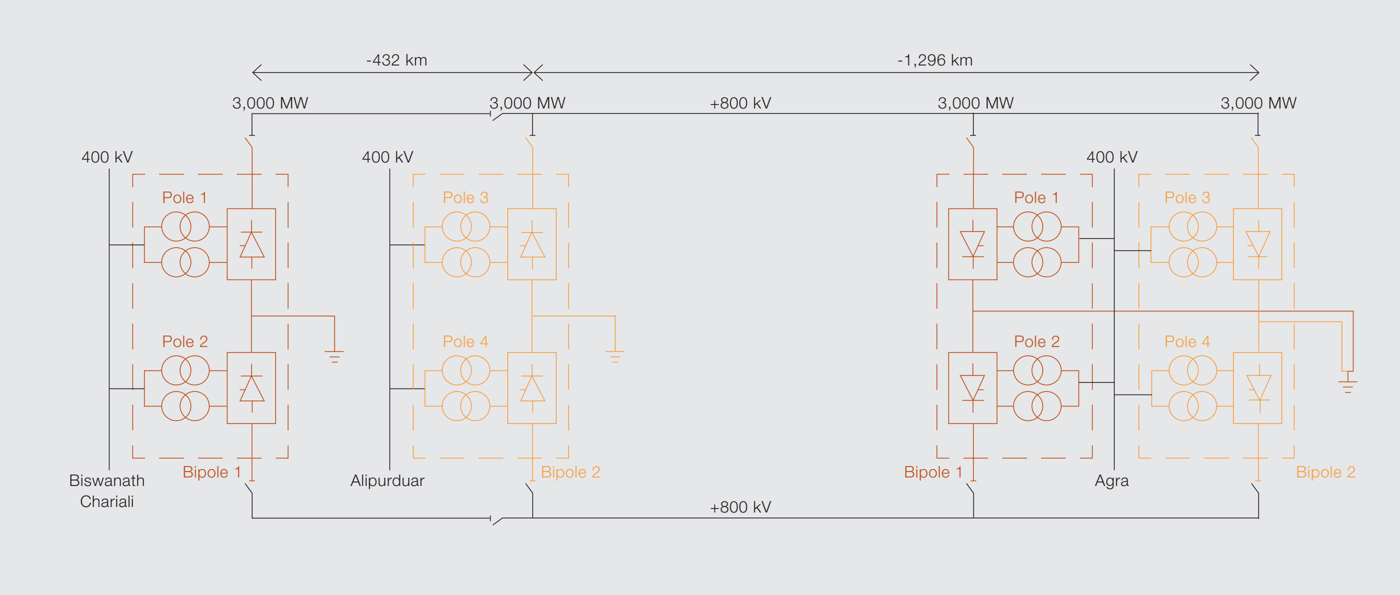
At full capacity, the North-East Agra HVDC link will be able to supply enough electricity to serve 90 million people based on average national consumption.

Multiterminal HVDC links are unique to ABB. The North-East Agra HVDC link will be the second ABB-built multiterminal HVDC link. The first of this kind was built by ABB in North America in the early 1990s. The Québec-New England HVDC link is a large-scale three-terminal transmission link (2,000 MW / 450 kV) commissioned in 1992. ABB recently received a contract to refurbish the 20-year-old control and protection systems of the link with the newest modular advanced control systems (MACH).

Railroad DC Tie

The Sharyland station, located at the border of Mexico and the southern tip of Texas in the United States, was the first 150 MW back-to-back DC tie station → 5. It was commissioned in 2007.

4 Multiterminal arrangement in North-East Agra HVDC link



5 Sharyland station

ABB designed a solution that includes unique black-start emergency assistance.

The Mexican and the Texan AC networks are not synchronized so connecting them as a normal AC interconnection was not possible. The Sharyland station enables power exchanges between the Electric Reliability Council of Texas (ERCOT) grid and the Mexican national grid, operated by the Comisión Federal de Electricidad (CFE), and increases power reliability in the Rio Grande Valley. HVDC technology enables bidirectional power flow between both grids, thereby allowing each grid to rely on the other in times of emergencies or peak demand.

ABB designed a solution that, in addition to the normal properties of an HVDC station, includes unique black-start emergency assistance. The solution also acts as a firewall, isolating disturbances and preventing them from spreading from one network to the other.

ABB is currently constructing a second 150 MW back-to-back HVDC converter station adjacent to the existing site. The two stations, part of the Railroad DC Tie Expansion project, will work in parallel to provide a transmission capacity of up to 300 MW. This will further increase the power transfer capacity between Texas and Mexico and secure the reliability of power in the Rio Grande Valley.

To learn more about ABB's reference projects, please visit www.abb.com/hvdc

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Steps beyond

ABB's HVDC Light® provides a range of expanded benefits for its customers

PETER LUNDBERG, MIKE BAHRMAN – Using advanced converter technology developed by ABB, the world's first HVDC transmission with voltage source converters began transmitting power in 1997. This technology was introduced as HVDC Light. The new transmission link ran along a 10 km route between the Swedish towns of Hellsjön and Grängesberg. It was rated at 3 MW / ± 10 kV DC. Due to its unique characteristics, HVDC Light has expanded the range of system applications beyond that possible with HVDC Classic. New uses include remote offshore applications, weak system interconnections, long land cables and black start. A look at a few of the significant HVDC Light projects tells the story of how ABB has linked the development of this technology to meeting customer needs.

1 Shoreham HVDC Light converter

Development of the new HVDC Light technology has continued at a rapid rate, with voltage levels and power ratings steadily increasing as power losses decrease. Since the first transmission ABB has undertaken 20 HVDC Light projects globally. HVDC Light is currently available for ratings of 2,000 MW / ± 500 kV in bipolar configuration and 1,200 MW / ± 320 kV in symmetrical monopolar configuration. Voltage source converter (VSC) technology provides superior dynamic features that go beyond pure power transmission. They have no reactive power demand or associated need for reactive power compensation. They appear to the network as a virtual synchronous machine but without inertia. Therefore the converters can help control the AC voltage.

A brief history

In the development of power electronic technology for industrial drive systems thyristors were replaced with VSCs where the semiconductors could be switched off as well as on. The advantages this change brought to controlling industrial drive systems could also be applied to transmission technology.

Title picture
ABB continues to develop HVDC Light transmission throughout the world.

The result was the development of devices with voltage and current ratings suitable for transmission. This semiconductor development formed the basis for HVDC Light.

Within five years of its inaugural project, ABB commissioned two HVDC Light commercial projects – Gotland Light in Sweden in 1999 and Directlink in Australia in 2002 – where the technology was proven at a voltage level of ± 80 kV and a power rating of 55 MW per circuit. The next step was the introduction of systems at the ± 150 kV level. A power rating of 330 MW was reached in 2002 with the Cross-Sound Cable (CSC) project connection in New Haven and Long Island in the United States, and the 200 MW Murraylink project in Australia.

Cross-border trading

With the CSC project, ABB showcased the ability for cross-border trading as well as excellent dynamic voltage support with HVDC Light. CSC was the first merchant transmission project in the United States consisting of a bidirectional 330 MW transmission system with two AC/DC VSC stations connected by a pair of 40 km DC submarine cables → 1 - 2.

Transmission capacity over the CSC project was offered to market participants through an open season process and a firm capacity purchase agreement. A key feature of the HVDC Light technology in the CSC project is the ability to precisely control power transfers with scheduled transactions by those who have purchased rights to its capacity.

Both interconnected networks benefit from active and reactive power control and AC voltage control.

Additional benefits for the HVDC Light technology in the project were reactive power and AC voltage control at each converter to support the connected AC networks and a compact layout with the majority of all equipment inside the converter building. Modular design allowed for comprehensive factory testing, which led to short field testing and commissioning.

2 The Cross-Sound Cable project links southern New England with Long Island, New York.

3 Estlink 1 HVDC Light cable laying

The cross-border trading feature in this instance works well because the operator can continuously control the power transfer in either direction between 0 and 330 MW independent of the AC voltage control. CSC manages the steady-state AC voltage regulation at the connecting stations to improve the dynamic stability. During the first year of operation a testimony to the quality of the feature was seen when a severe thunderstorm on Long Island created multiple AC faults, yet voltage up to its reactive power limit of 125 MVAr was supported and active power kept relatively constant.

Following the massive blackout of the northeastern portion of North America on August 14, 2003, CSC was instrumental in restoring electric power to customers on Long Island, being one of the first transmission links to the area brought into service after the blackout. The link transported 330 MW to the area, enough power to restore electric service to over 330,000 homes. Furthermore, CSC's AC voltage control feature proved valuable by stabilizing the AC system voltage in Connecticut and on Long Island during the network restoration.

Estlink 1

Supply security and black-start capability are additional benefits ABB has provided with HVDC Light. The Estlink 1 transmission system, operating at 350 MW / ±150 kV DC, has been able to provide these features while connecting the national grids of Estonia and Finland. Commissioned in December 2006, this was the first time electric power was exchanged between the Baltic states and the Nordel electric systems. With the goals of creating electricity trading and increasing secure supply in the Baltic region, HVDC Light was an obvious choice due to the asynchronous networks and the long distance under water between the two systems ➔ 3.

Both interconnected networks benefit from active and reactive power control and AC voltage control. Additional control features are emergency power control, frequency control and rapid active power flow to support either of the connected grids. On the Finnish side a damping control is designed to damp the inter-area oscillations that can occur in the Nordel electric system to increase operational security.

HVDC Light converters are able to generate a voltage that can be changed very quickly in amplitude and phase and offer the possibility of energizing a network after a blackout. This has been implemented in Estlink 1 for the Estonian side.

The transformer is equipped with a special auxiliary power winding for self-supply of the converter station, and the control system has schemes for detecting a network blackout. If such a blackout occurs, the converter will automatically trip the connection to the grid, and continue to operate in supplying its own auxiliary power, supplied through the DC from the Finnish station. The converter can also be started manually in black-start mode, if needed.

The network restoration sequence starts with the converter station running without load. The voltage and frequency are decided by the converter, which in this case operates in voltage and frequency control. The AC network is then connected with a small load, and ramped up to the rating of the link. The black-start feature makes it possible to start up parts of the Estonian network in only minutes after a total blackout. In the network restoration scenarios determined by the grid operator, Estlink 1 would provide auxiliary power to selected power units. Estlink 1 and the connected generators will share the load through the use of frequency droop. When a sufficient amount of generation is feeding the network, the mode of operation of the converter can be changed from frequency/voltage control to normal power/voltage control.

Caprivi Link

Many of the electricity networks in the developing part of the world, such as Africa, span vast distances and are often characterized by relatively weak AC networks. ABB's Caprivi Link project[1] was able to meet these challenges in order to connect the Zambezi converter station in the Caprivi strip in Namibia, close to the border of Zambia, and the Gerus converter

4 Gerus HVDC Light station

Additional customer benefits are the system's black-start capability and active AC voltage support.

station, about 300 km north of Windhoek in Namibia → 4. The Caprivi transmission link is a 2 × 300 MW interconnection with the converter stations joined by a 950 km long, bipolar ± 350 kV DC overhead line. This was the first HVDC Light project to combine VSCs with overhead lines.

The weak networks have a high likelihood of becoming islanded with passive AC networks when critical lines are tripped. The converter controllability with AC voltage and frequency control prevents tripping of about 100 MW of generation at Victoria Falls island close to the Zambezi converter. A similar condition can occur on the Namibian side when the AC link to South Africa is lost and the Gerus converter station islands together with the Ruacana hydropower station. Similarly both sides can experience passive network conditions where no generation is present. Without the HVDC Light link the outage of critical lines can lead to a blackout due to the extremely weak AC network.

The HVDC Light solution has enhanced stability and assisted with the prevention of blackouts. The Caprivi Link converter stations can provide up to ± 200 Mvar reactive power capability throughout nearly the entire power transfer range from 0 to 300 MW. The solution is prepared for providing n-1 network security when the full bipole is implemented. During a DC line fault, the converter stations are temporarily isolated from the AC grid and the DC line by opening the AC and DC circuit breakers to interrupt the fault currents. Immediately after clearing the fault currents, the breakers are re-closed and the transmission resumed. Reactive power support is resumed within 500 ms and power transmission within 1,500 ms.

Intergration of onshore renewable generation

HVDC Light transmission technology is of particular interest for power transfer between asynchronous AC grids in order to increase the security of supply between grids with wind farm generation. The EirGrid East-West Interconnector project (EWIP), is a benchmark example. Commissioned in 2012, EWIP links the high-voltage power grids of Ireland and Great Britain by means of an HVDC Light interconnection. The project is ABB's most recent, and largest HVDC Light project undertaken.

Ireland is expanding its wind power generation and the 500 MW / ± 200 kV EWIC HVDC Light transmission system provides an opportunity to export excess power into the UK market.

Additional customer benefits, due to the choice of the HVDC Light technology, are the system's black-start capability and active AC voltage support. In addition, by connecting to the UK national grid, Ireland can now access power from continental Europe (via an interconnector from Great Britain to the continent).

As part of the solution, ABB extended the previous rating record for an HVDC Light cable from 150 kV to 200 kV. The higher voltage enables a higher transmission capacity of 500 MW.

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Footnote

1 See also figure 3 on page 35 of this issue of *ABB Review*.

AC/DC

Backing up AC grids with DC technology

STEFAN THORBURN, TOMAS JONSSON – As the demand for energy grows, so too does the demand for reliable supplies of energy. When power grids were established, AC transmission was the preferred choice, overcoming DC's inability to be quickly interrupted and transformed. Now, more intelligent, better-controlled networks are needed. How can these be created? The key lies in combining existing AC and DC technologies, making use of the best of both. HVDC (high-voltage direct current) transmission will be embedded inside the AC grid and will reinforce the operation of the whole grid with its controllability, speed and low losses. At designated locations the HVDC system will operate as a "firewall," supporting the AC system during disturbances.

HVDC transmission is starting to evolve into a grid of its own where very fast HVDC breakers help maintain high availability of the meshed HVDC grid. The existing AC system is utilized to transform power between different voltage levels and to use the less costly AC breaker for local fault clearance, minimizing the impact of an electrical fault.

Reinforcing the AC grid

The existing point-to-point HVDC links already show many examples of support functions, which can, even today, become part of a wider HVDC grid [1]. These support functions address four main constraints in the AC system:

- There must be a power balance between production and consumption (including losses).
- Thermal overloading of the circuits must be avoided.
- The synchronous generators must be in synchronism. If they are not, there may be difficulty maintaining the integrity of the AC system after an electrical fault or avoiding oscillations between the generators.
- Availability of local reactive power control must be ensured. Losing this control may result in a voltage instability, which could spread and endanger the whole power network.

There are also different ways in which AC and DC systems can be connected. The HVDC system can be embedded in the AC system or it can connect separate AC systems → 1 – 2. In the embedded HVDC grid, the AC frequency is the same in all HVDC stations. A power imbalance in the AC grid cannot be alleviated by HVDC control since both ends of the HVDC link are in the same grid. With DC and AC grids in parallel, the AC frequency is the same in the HVDC stations, but the HVDC system is in a strong position to mitigate an existing bottleneck on the AC side. With separated AC grids, the AC frequency differs between the HVDC stations; a power imbalance in one of the AC grids can be alleviated by applying proper HVDC control. The size of the HVDC support can easily be limited to the present capacity (spinning reserve) of the other AC grid.

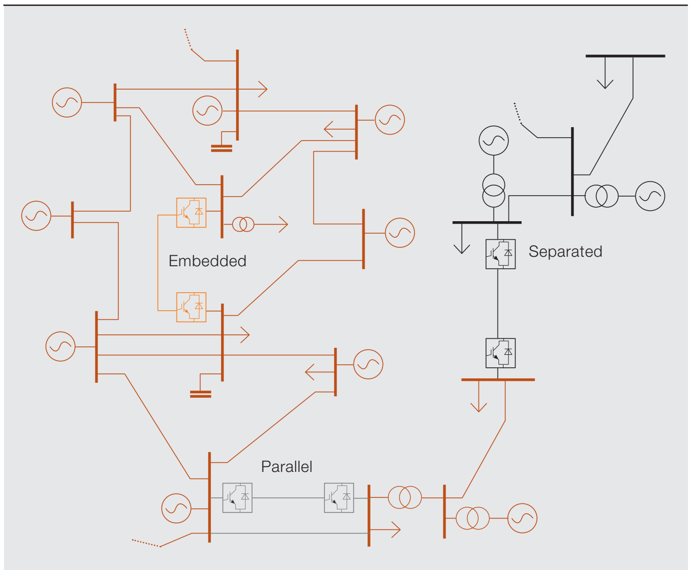
HVDC as a firewall in the AC grid

An HVDC system can be placed between AC grids as a firewall to prevent disturbances spreading from one AC grid to another. The HVDC system can be set up such that loop flows are avoided and market power exchange can be fulfilled. Should a power imbalance occur on the AC side, HVDC control can mitigate the imbalance and borrow spinning reserve from the neighboring AC systems in a controlled manner.

Frequency stability

An imbalance between the produced and consumed power will show up as a frequency deviation. Many HVDC systems can mitigate the frequency devia-

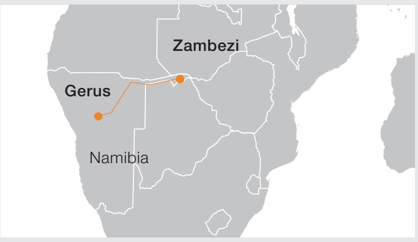
1 Connecting AC and DC systems



2 Level of support possible from an embedded HVDC system during disturbances

	Embedded HVDC grid		Separated AC grids	
	VSC	Classic	VSC	Classic
Operate as a firewall during contingencies	+	0	+++	++
Maintain frequency stability	N/A	N/A	+++	+++
Artificial inertia	N/A	N/A	+++	+
Maintain synchronism	++	+	+	+
Improve voltage stability	+++	+	++	+
Improve power oscillation damping	++	+	++	+
Merchant links	++	++	+++	+++
Black start	+	0	+++	0

3 Case study: Caprivi Link



The Caprivi Link interconnects the Namibian and Zambian/Zimbabwean AC systems ➔ 4. The overhead HVDC line has a length of 952 km. The first stage of the project was a monopole scheme with a nominal power of 300 MW and nominal DC voltage of -350 kV DC.

At the initial stage, the AC networks at both sides are extremely weak and the short-circuit ratio (SCR) at the connection points may be below 0.8. Normally, the AC networks at both sides of the HVDC link are connected to the AC grid of South Africa, resembling a parallel AC structure as in ➔ 1. However, if an AC line is lost it can lead to an islanded network situation in either end of the HVDC link.

For islanded network situations, the converter station has a characteristic comparable to an infinite AC source, ie, a slack bus. The link automatically converts the active power needed to maintain the power balance of the system. It also automatically converts the reactive power needed to keep the AC voltage at the desired level. Under normal AC network conditions, the converter resembles an electrical machine to generate or consume active and reactive power.

Performance under islanded AC network in Namibia

On June 3, 2010, a high-power transmission was planned from Namibia to Zambia. During the process of ramping up power, when the power exported from Namibia was about 80 MW, an overload protection tripped a 220 kV line in Nampower's 220 kV bus zone, which led to an islanded condition in Namibia.

This unplanned event was observed and automatically recorded in both converter stations ➔ 5. The Gerus substation (shown on page 33 of this issue of *ABB Review*) immediately reduced the power to almost zero (see the lower plot in ➔ 5a). About 1 s after the line tripped, the Namibian grid restored stable AC voltage and frequency [2].

tion if one of the converters is connected to a separate AC grid. Assuming that the separate AC grid has spinning reserve available, the stressed grid can be automatically supported to restore frequency stability.

Artificial inertia

In very weak AC systems, frequency variations may be a problem due to the low ratio of rotating mass (inertia) related to synchronous machines. An HVDC link in such an AC system can be controlled to provide additional inertia in order to strengthen the local stability. Such functionality has been implemented in the Caprivi Link project in southern Africa ➔ 3.

Maintaining synchronization

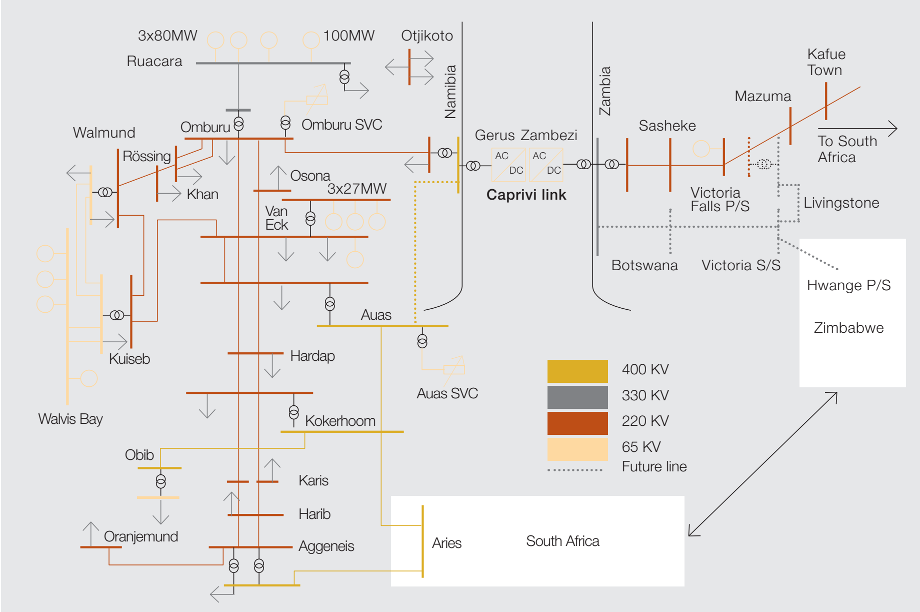
To maintain synchronization, the HVDC system will support the AC system in several ways. For example, during a fault, the VSC (voltage source converter) technology will start to back up the AC system. When the fault is cleared, the reactive power output from the HVDC system will support the power transfer in the AC grid. This will reduce the risk of falling out of step and losing synchronization. Special schemes can be set up in the HVDC system to help quickly restore a viable power flow after a fault.

It is also possible to control the HVDC system in such a way that inadvertent power flow changes in the AC grid are automatically compensated for so that a safe power transfer can be maintained in the AC system. The active power control can, alternatively, be set up such that it resembles the phase-angle dependency of an AC line (possibly with reactive power support at each end).

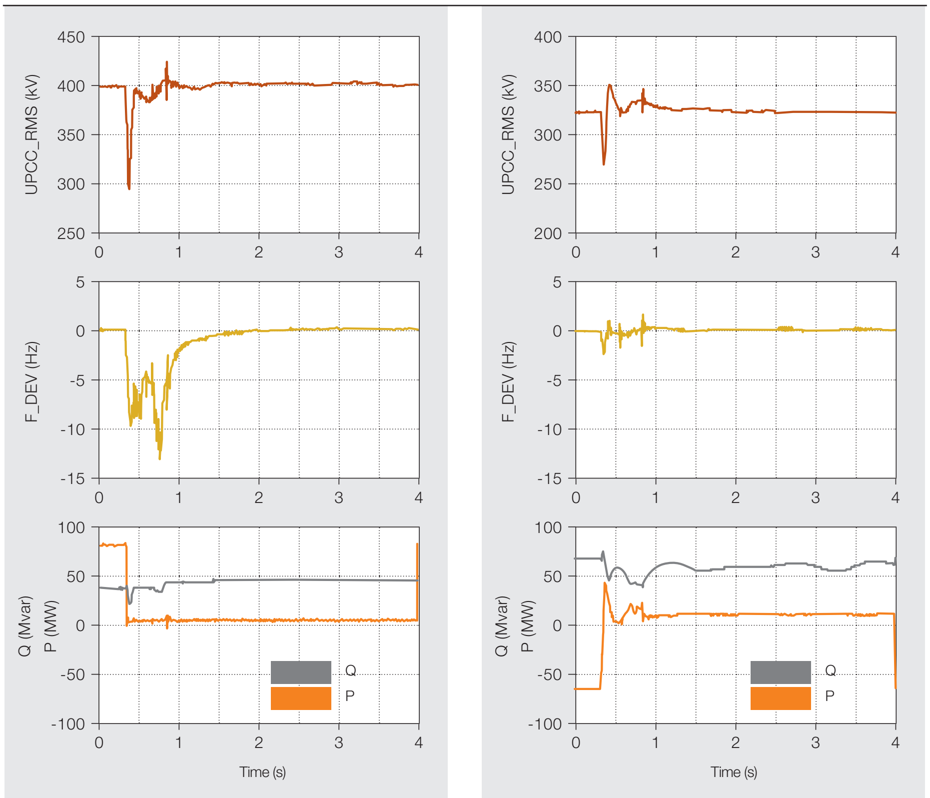
Power oscillation damping

A stressed AC system is prone to electromechanical oscillations of the rotors in the synchronous machines. This is an unwanted situation since it wears down the governor systems of the turbines and indicates an operating working point close to the stability limit related to maximum power transfer. By modulating a control signal to the HVDC system, oscillations can be damped and a safe power transfer limit can be maintained in the AC system. This damping functionality has been implemented in several links, including the Pacific DC Intertie and the Fenno-Skan link.

4 Network map of the Caprivi Link project



5 AC voltage, frequency and converter P/Q loadings for Zambezi and Gerus



5a Gerus

5b Zambezi

Black start

In some AC grids, black-start functionality is very valuable. The restoration process (black start) of an AC system following a contingency related to loss of crucial AC lines, islanding or blackout has some critical requirements, which, in certain cases, can be fulfilled with an HVDC link. VSC transmission technology is particularly suitable. The VSC link can follow the cold load pickup and the pickup of the power production with its smooth control of both active and reactive power. As the AC grid is rather weak and often has reduced short-circuit power during a black start, high requirements are put on reactive power control to maintain voltages. ABB has implemented and tested this for the Estlink 1 project.

Merchant links

The coupling of electricity markets and growing commercial interconnections requires precise, controllable power flows in order to operate effectively in line with the market-derived schedules. Power scheduling on an hour or minute basis is a common situation. The controllability of active power flow in the HVDC system compensates for the power flow in the AC system that would follow the physical laws rather than the prearranged commercial deals.

AC/DC: the grid of the future

The HVDC system will alleviate power imbalances in the AC system and give operators full control over the power flow. With the introduction of VSC technology, HVDC is also able to operate as a FACTS[1] device. The HVDC system can consist of a back-to-back converter, a point-to-point connection, a multi-terminal connection, or a meshed HVDC grid with parallel paths enhancing the availability of the HVDC system.

For more information, please visit
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[1] S. G. Johansson, *et al.*, "Power System Stability Benefits with Vsc Dc-Transmission Systems," CIGRE, Paris, 2004.

[2] Y. Jiang-Häfner, M. Manchen, "Stability Enhancement and Blackout Prevention by VSC Based HVDC," CIGRE, Bologna, 2011.

Footnote

1 FACTS, or flexible alternating current transmission systems, are technologies that enhance the security, capacity and flexibility of power transmission networks.

Offshore power

With HVDC Light® ABB offers the off-shore industry an alternative way to provide electrical power to platforms

MATS HYTTINEN – Traditionally, offshore platforms generate their own electricity by burning fossil fuels to run onboard gas turbines and/or diesel-powered generating units. This inefficient method has come under increasing scrutiny and criticism because it creates substantial greenhouse gas emissions, particularly CO_2; consumes large amounts of fuel; and adversely impacts the health and safety of platform workers. Some regions also put a high tax on CO_2 emissions, adding to the steep operating costs of platform generating systems. ABB's HVDC Light is a proven technology providing more efficient power from shore for customers who need reliable power in remote places. As the offshore industry searches for alternative ways to provide platforms with electrical energy, ABB is ready with a solution.

1 The Troll A was the first HVDC Light transmission system installed in an offshore platform.

ABB's HVCD Light is a robust transmission system with a long life cycle that reduces operating and maintenance costs. Such a power-from-shore system helps make the platform a safer, cleaner place to live and work by lowering greenhouse gas (GHG) emissions, risk of fire and explosions on the platform, and noise and vibrations, while maintaining the highest standards of reliability and availability.

Ensuring high availability and lower costs

The offshore industry's main requirement of any power supply solution is high availability, since an emergency shutdown means loss of production capacity and income.

An HVDC Light installation typically has 99 percent availability per year, taking into account both scheduled and forced outages. The lifetime is on average 30 to 40 years, which is higher than a local generation solution. Efficiency rates vary depending on the transmission distance and cable type. With an HVDC Light transmission system there is often more than a 90 percent efficiency rate, compared with the typical range of 15 to 25 percent for a local generation unit.

Coupled with the requirement of high availability is the cost-effectiveness of the transmission system. Each potential user of HVDC Light for offshore power is unique in terms of power rating, distance from the platform to the mainland, sea depth, etc. Initially the cost to install generation on the platform can be lower than the cost to install a power-from-shore system, especially when power ratings are low, the sea route is deep and the distance from the mainland is long. However, by using an electricity supply from the mainland weight and volume on the platform are greatly reduced, enabling significant savings in the long term. A small and compact HVDC Light solution may also enable a complete onshore assembly, with shorter installation and commissioning time, thus further reducing costs.

In terms of operating costs power-from-shore alternatives require less maintenance and shorter maintenance shutdowns. Power-from-shore solutions produce no emissions, so an emissions tax is not paid.

From a health and safety perspective, power-from-shore eliminates all hazards associated with gas-fired rotating equipment operating in the vicinity of platform workers. The reduced risk of a fire or explosion, as well as decreased noise levels and vibrations, are also important workplace improvements.

Technical background

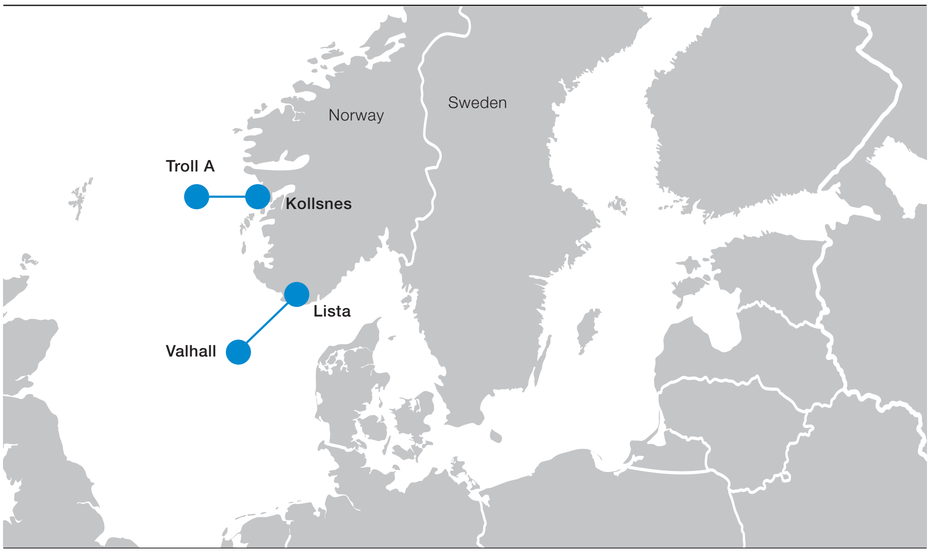
Initially power-from-shore solutions were limited to AC cable systems over short distances (50 to 100 km), or conventional line-commutated HVDC systems. The introduction of HVDC Light with voltage source converter (VSC) technology in the late 1990s opened up the market segment, because VSC technology enables a cost-effective supply of large amounts of power over long distances using robust, lightweight, oil-free cables. Beyond 50 to 100 km, HVDC Light is the only technically feasible solution.

HVDC Light does not need any short-circuit power to operate, which makes it an ideal technology to start up and energize offshore platforms and allows for fully independent control of both active and reactive power. The technology ensures smooth energization and startup, and precise control of the platform's power system.

During a black start, active and reactive power is automatically adjusted according to the ongoing power need of the platform. The HVDC Light link will balance the load generation automatically as new loads are connected, instantly changing the transmitted power according to the size of the load.

Title picture
Valhall HVDC Light field platforms

2 Troll A and Valhall transmission links



Each potential user of HVDC Light for offshore power is unique in terms of power rating, distance from the platform to the mainland, sea depth, etc.

The optimum balance between the size of the platform module, equipment cost, engineering work and risks must be evaluated in each specific installation. Specific arrangements and optimizations of the main circuit equipment may be necessary to achieve desired compactness.

In addition, the system design must ensure that maintenance activities have an absolute minimum effect on system operation. With HVDC Light, maintenance time – especially work that requires interrupting the power transmission – can be minimized by exchanging whole modules or components, instead of repairing them, and by introducing redundant systems whenever technically or economically justified.

Troll A

The Troll A precompression project delivered to Statoil in the North Sea and commissioned by ABB in 2005 was the first HVDC Light transmission system ever installed in an offshore platform ➔ 1. It is located in the Troll oil and gas field about 65 km west of Kollsnes, near Bergen, Norway ➔ 2. This field contains almost 40 percent of total gas reserves on the Norwegian continental shelf, and is the cornerstone of Norway's offshore gas production.

The groundbreaking solution delivers two independent systems, each producing 42 MW of power from the Norwegian mainland to power a high-voltage variable-speed synchronous machine installed on the platform to drive compressors that maintain gas delivery pressure, compensating for falling reservoir pressure.

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

The electrical drive system that Statoil and ABB developed has met all performance expectations. The ABB motorformers – a very-high-voltage motor and generator – installed on a platform compressor skid have performed well and operate at lower than expected vibration levels.

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

Valhall

The Valhall HVDC Light power-from-shore transmission system was commissioned in October 2011 to replace gas turbines on British Petroleum's (BP) linked multi-platform complex in the North Sea, about 294 km from the Norwegian mainland ➔ 2. The Valhall HVDC Light system is capable of delivering 78 MW to run the offshore oil-and-gas field facilities, though most customers need only roughly half the power.

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

According to BP the benefits gained from using ABB's HVDC Light power-from-shore technology, as opposed to conventional gas-turbine generators, are considerable. Operating and maintenance costs have been significantly lowered. Each year 300,000 t of CO_2 and 250 t of NO_x emissions have been eliminated. Working conditions have improved and no emissions tax is applied. Maintenance is minimal, simple, remote and safe, which reduces the need for the constant presence of offshore crews.

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First-class service

Service and upgrades lengthen HVDC equipment lifetime and maximize performance

ANNA JANSSON, HANS BJÖRKLUND – High-voltage direct current (HVDC) transmission links are being used all over the world to efficiently and cost-effectively transmit large amounts of power from generators to distant centers of consumption. But such links represent significant investments for the utilities who own them. Also, HVDC assets typically have an expected lifetime that runs into decades. These two aspects of HVDC mean that properly servicing and upgrading these assets is of major importance. ABB has extensive experience with HVDC service – covering regular maintenance and support as well as major service and upgrades. Control system upgrades, which can be done with a relatively short system outage, are, in particular, an efficient way to prolong the high performance of an HVDC link. Service, maintenance and upgrades have been applied by ABB in many cases to maximize output, increase functionality and extend the lifetime of HVDC assets.

1 ABB has many years of experience in HVDC and has maintenance and service agreements with many HVDC systems operators.

When an HVDC transmission asset has a lifetime of many decades, then very often newer, better technology has come along by the time the asset has reached the middle of its expected lifetime. Carrying out an upgrade at this point can add many years to the asset's lifetime as well as further increase its availability and reliability. ABB has a long experience with HVDC and is trusted by many operators of HVDC systems with maintenance and service agreements → 1. One recent example of a long-term service undertaking that typifies this sort of arrangement is found in the Estlink 1 HVDC Light project, where ABB has been providing services since the commissioning of the link in 2006.

These consist of:
- HVDC converter station operation support, eg, weekly inspection of unmanned stations
- Regular preventive and corrective maintenance
- Annual planned maintenance
- 24/7 standby
- Spare parts and other additional services
- Control system maintenance

Title picture
HVDC equipment, like this converter station in Finnböle, Sweden, represents a significant investment. Servicing and upgrading can ensure that the operator gets the most out of the equipment as well as extend its life.

Assessments maximize system lifetime and reduce downtime

In order to put a coherent service and upgrade plan in place for HVDC equipment, it is usually necessary to perform a lifetime assessment of certain systems or items of equipment. Such an assessment is available for all HVDC-specific equipment provided by ABB – eg, converter transformers, thyristor valves, IGBT valves and control equipment. Similar assessments can also be carried out on conventional AC equipment included in the HVDC scheme – eg, breakers, disconnectors, filter reactors and cables → 2. These assessments provide the owner with a firm foundation upon which planning for future upgrades, service and operation can be based.

ABB has a long experience with HVDC and is trusted by many operators of HVDC systems with maintenance and service agreements.

Midlife upgrades of HVDC installations

When built, most HVDC installations had a long operational life - typically 30 years – as a design target. When the end of this design life nears, it often turns out that the installations are still running very efficiently and delivering substantial economic benefit to their owners. Often, many important parts – usually representing the bulk of the investment – are still in good working order and can be used for many more years to come. Examples of these are overhead lines, cables, buildings, switchyards and transformers. When elements of these assets, such as breakers, parts of a cable or single-phase transformers, fail, they can often be replaced on component basis. However, there are some parts of an HVDC installation that need to be viewed as an integrated system and for these it is advantageous to look at a more coordinated upgrade activity.

Upgrades of control and protection systems

The lifetime of an HVDC control and protection system can be expected to be at least 30 years. The actual life is often longer, perhaps 40 years, but for installations that will operate for 50 to 60 years it is wise to plan for one replacement of the

2 Breakers at Porto Velho HVDC station

3 Control and protection upgrades

Station	Year commis-sioned
New Zealand pole 1 and 2	1992
CU	2004
Square Butte	2004
Sylmar converter station, Pacific DC Intertie	2004
Skagerrak 1 and 2	2007
Apollo converter station, Cahora Bassa HVDC link	2008
Blackwater	2009
Chateauguay	2009
IPP	2010
Highgate	2012
FennoSkan 1	2013
The following stations are currently being prepared for control upgrades:	
Eel River	2014
Skagerrak 3	2014
Inga Kolwezi	2014
Celilo converter station, Pacific DC Intertie	2015
Quebec New England multiterminal HVDC	2016-17

control equipment during the lifetime of the plant – perhaps after about 20 to 35 years. In this way, an optimal return on investment for the new controls can be achieved. If the plan is to retire the complete plant after 40 years, the control equipment can most likely be used during the entire operational lifetime of the plant if the spare part supply is monitored closely during the last years of operation.

Some parts of an HVDC installation need to be viewed as an integrated system and for these it is advantageous to look at a more coordinated upgrade activity.

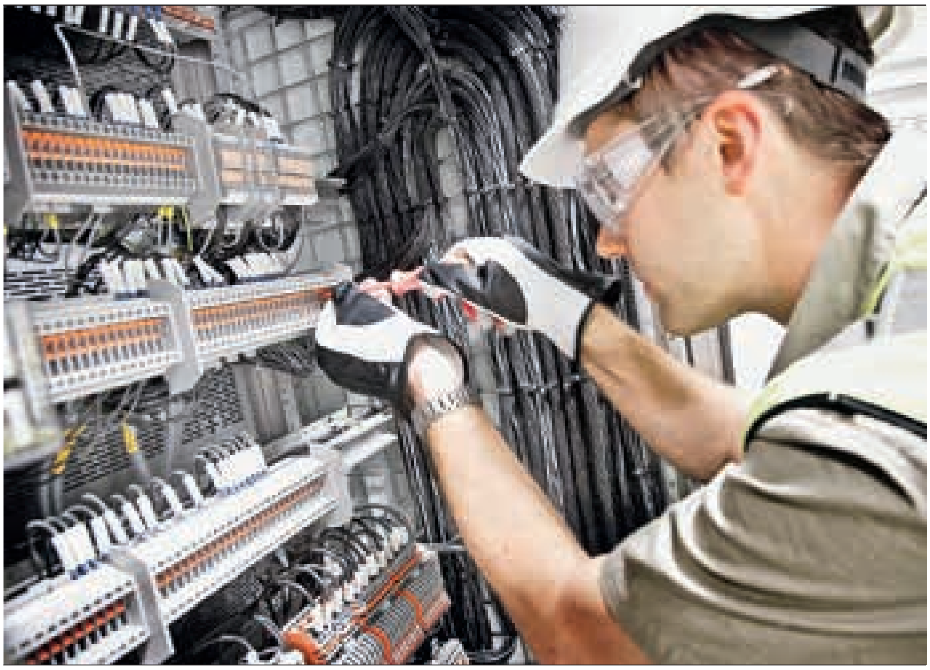
These assumptions are supported by data from the large number of plants around the world that have long service histories and by the different reasons for upgrading their control and protection systems.

A complete control equipment upgrade essentially means replacing the brain of the converter; this will inevitably result in power transmission being interrupted at least for one pole at a time. The cost of this period of unavailability may be as much as, or higher than, the actual upgrade and ABB has therefore focused both the design of new control and protection systems and the organization of the upgrade work on keeping outage times to a minimum.

One example of this type of work is the recent successful upgrade and testing on Great River Energy's CU HVDC project – a 1,000 MW / ± 400 kV DC bulk power transmission corridor between Underwood, North Dakota and Dickinson, Minnesota, that was built and commissioned by ABB in 1978. Here, the controls were changed with just a two-week outage of one pole at a time while the other pole of the bipole was running. Thus, the complete bipole could be upgraded in one month, during which time the HVDC link could still carry 50 percent of its rated power.

In the Intermountain Power Project (IPP) in the United States, commissioned in 1986 to bring power from a 1,600 MW coal-fired generating plant in Utah to Southern California, a similar approach was used but here a three-week outage per pole was needed because not just the control system, but also the valve cooling and the transformer cooling sys-

4 MACH control system



In due course, upgrades of IGBT valves will be available in ways similar to that of thyristor valves.

tems were upgraded to handle higher powers.

In Skagerrak 1 and 2 – HVDC links between Norway and Denmark – a different approach was used because maintenance work on the overhead line was needed and this required a bipolar outage. A three-week bipolar outage was planned, but the installation activities went very smoothly and power transfer was restarted after an outage of just 15 days.

There are many such examples of completed control and protection upgrades → 3. ABB's long experience in HVDC and the very advantageous structure of the MACH control system → 4 stands ABB in good stead when such upgrades are executed.

Thyristor and IGBT valve upgrades

Remarkably, most of the HVDC thyristor converters ever supplied by ABB/ASEA are still in operation. From the technical data available, it can be concluded that the lifetime of a thyristor valve is very long, probably around 50 to 60 years.

Because thyristor technology has advanced so dramatically in the last 40 years, replacing an old thyristor valve with a new one may be a good business proposition for the customer, resulting in life extension, lower losses and decreased maintenance. ABB has a leading position in this area and has conducted valve upgrades in the Sylmar, Apollo, Inga and Kolwezi converter stations. Future valve upgrades are being prepared for the Eel River and Celilo HVDC converter stations.

So far, IGBT valves (the successor to thyristor valves) have only been in operation for 15 years. In due course, upgrades of IGBT valves will be available in ways similar to that of thyristor valves.

The further development and improvement of ABB's HVDC service product portfolio is very important and is an ongoing exercise. For example, ABB is placing great emphasis on Web-based systems that speed up support and service information exchange between customers and ABB. Further, an annual users' conference (celebrating its 21st anniversary this year) ensures that customer feedback is clearly understood and mutual proposals for service improvements can be heard. These and many more measures that enhance upgrades and service ensure a commitment to quality throughout the entire life cycle of a product.

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A single-source supplier

ABB enjoys a unique position in HVDC systems technology, being the sole company able to supply all key components. An HVDC substation includes converter valves with power semiconductors, cooling equipment, transformers, bushings and other DC and AC power products, and in many cases, cable connections.

Heart of the converter

High-voltage power semiconductor devices

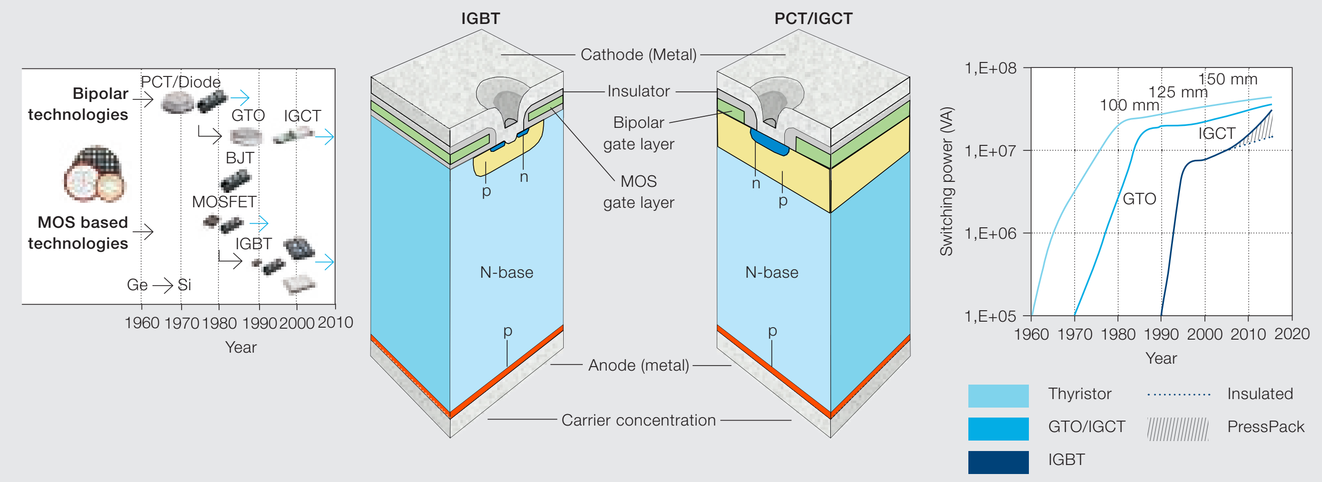
MUNAF RAHIMO, SVEN KLAKA – Silicon-based high-voltage semiconductor devices play a major role in megawatt power electronics conversion. In particular, advances in ultrahigh-voltage semiconductors have over the past few decades led to tremendous improvements in high-voltage direct current (HVDC) transmission. The power device is considered a main enabler for the growing demands of modern grid systems in terms of increased power levels, improved efficiency, greater control and integration of renewable energy sources.

The power electronics revolution, which over the past few decades has swept across the power delivery and automation sectors, has opened up a wide range of possibilities in terms of controlling the way electrical energy is transported and used. At the heart of this revolution lies the power semiconductor device: This device performs the actual task of modulating the energy flow to suit the demands of the application. The main trend in the development of power devices has always been increasing the power ratings while improving overall device performance in terms of reduced losses, increased robustness and better controllability, and improving reliability under normal and fault conditions.

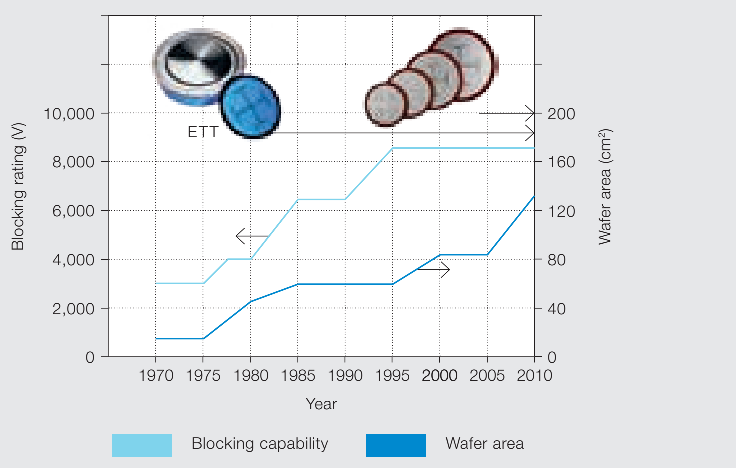
The HVDC-applications market is small but important for semiconductors. Progress in the domain of power devices has in the past largely been dependent on technologies developed for lower power applications, which were then scaled to handle higher voltages and currents. In HVDC applications today, the two main types of switching devices are the phase-controlled thyristor (PCT) and the insulated-gate bipolar transistor (IGBT). Also important is the power diode found in a range of applications spanning rectification, snubber and freewheeling.

Different power-semiconductor-based circuit topologies such as current source converters (CSCs) and voltage source converters (VSCs) are employed for the AC/DC conversion process. For long-distance and multi-gigawatt power transmission, PCT-based CSC topologies are widely

1 Power device evolution and basic structures



2 PCT evolution and 150mm PCT rated at 8.5 kV / 4,000 A for UHVDC



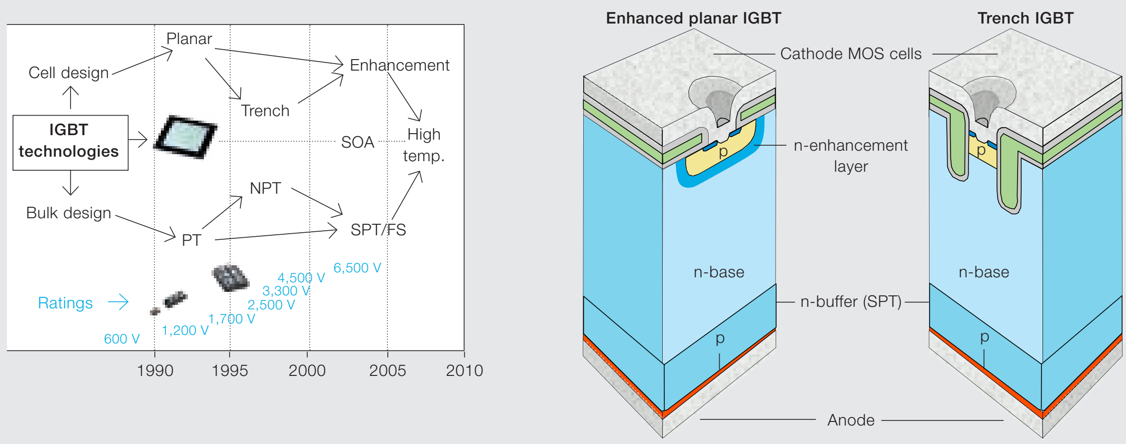
The power electronics revolution has opened up a wide range of possibilities in terms of controlling the way electrical energy is transported and used.

used due to the overall low system losses. For relatively shorter distances and lower power levels, IGBT-based VSC conversion is becoming the system of choice due to a number of advantageous integration and control features (especially when taking into account the introduction of renewable energy into the grid). Despite the existence of optimized high-voltage devices with attractive electrical characteristics, the main development trend continues to seek higher power and superior overall performance.

Power semiconductor devices for HVDC applications

High-voltage power semiconductors differ from their low-voltage counterpart in a number of structural aspects. First, they include a wide and low n-doped base region at the pn-junction to support the high electric fields required for the high voltage ratings. For current-carrying capability with low losses, they require large active areas and highly doped contact regions to provide high minority carrier (holes) injection levels for modulating the low doped n-base, and good ohmic contacts to the outside world. Current normally flows in the vertical direction (perpendicularly to the wafer surface) in devices whose voltage range exceeds 1 kV. Today, silicon-based devices can be designed with good overall performance parameters up to 8.5 kV for a single component. It is important to note here that power semiconductors employed in grid systems do not differ from those

3 Evolution of IGBT technology and modern structures



For relatively shorter distances and lower power levels, IGBT-based VSC conversion is becoming the system of choice.

employed in other power electronics applications such as traction and industrial drives.

Nevertheless, for HVDC applications operating in the hundreds of kilovolts range, devices are normally connected in series to support the total DC-line voltage. The choice of the single device voltage rating employed in these systems depends largely on the performance/cost calculation for a given topology and operational parameters. Devices rated for lower voltages normally have favorably lower overall loss figures but imply that a larger number of components are needed.

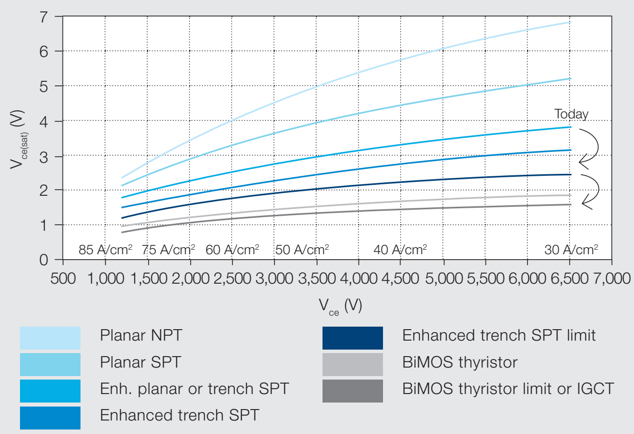
The basic structure of a PCT and IGBT is shown in → 1 as is its evolution over the years along with other device concepts such as the integrated gate-commutated thyristor (IGCT). The historical increase in the switching power levels of high-voltage devices is also shown. The PCT is a thyristor bipolar device, which is mainly characterized by its favorable excess carrier distribution for low on-state losses in conduction mode. The IGBT, on the other hand, is a MOS (metal-oxide semiconductor)-controlled device with a bipolar effect for achieving low on-state losses.

The PCT

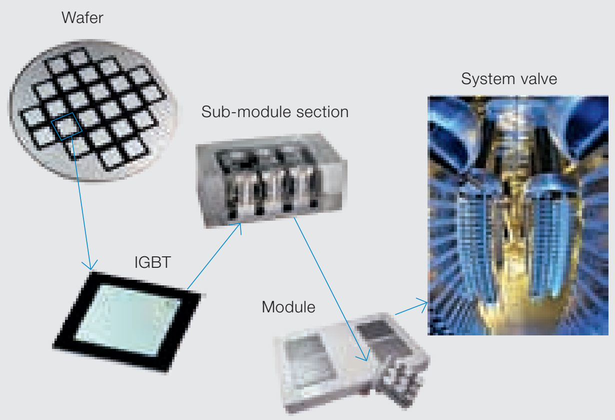
In contrast to the IGBT, the PCT is not a turn-off device. It is nevertheless the device of choice for line-commutated CSC HVDC systems due to its exceptionally low on-state losses and very-high-power handling capability. Until very recently, state-of-the-art single devices were rated at 8.5 kV with a total diameter of 125 mm. With the increase in demand for even higher power HVDC system ratings, larger area 150 mm, 8.5 kV PCTs with current ratings up to 4,000 A were developed for the latest Ultra HVDC systems operating at ± 800 kV with total transmission power exceeding 7 GW. The PCT evolution, including the new 150 mm PCTs and the UHVDC system valves consisting of series connected PCTs, is shown in → 2.

The PCT is the device of choice for line-commutated CSC HVDC systems due to its exceptionally low on-state losses and very-high-power handling capability.

4 High-voltage IGBT technologies on-state losses $V_{ce(sat)}$



5 IGBT application from single chip to system valve



Further technology developments are underway to increase current ratings to exceed 6,000 A while lowering conduction losses.

The IGBT

The IGBT is a MOS-controlled bipolar switch and presents the inherent advantages of that technology including a controlled low-power driving requirement and short-circuit self-limiting capability. The IGBT has experienced many performance breakthroughs in the past two decades ➔ 3.

The fast progress in IGBT cell designs (planar, trench, enhancement layers) and bulk technologies such as punch-through (PT), non-punch-through (NPT) and soft-punch-through (SPT) has led to their widespread deployment in many high-voltage applications. Today, high-power IGBT press-pack and insulated modules have ratings ranging from 1,700 V / 3,600 A to 6,500 V / 750 A. The most recent trends have targeted lower losses by using thinner n-base regions (SPT) and plasma enhancement layers and/or trench cell designs as shown in ➔ 3 accompanied by higher SOA and higher operating temperature (HT) levels. Similar development efforts targeted an improved diode design to match the latest IGBT performance. The freewheeling diodes play a very important role in the application during normal switching and under surge current conditions. The current IGBT platform employed in grid applications is based on an enhanced-planar cell design (EP-IGBT), which has enabled the establishment of a new technology curve benchmark over the whole IGBT voltage range from 1,200 V up to 6,500 V as shown in ➔ 4. Future higher power densities and loss reductions are possible by implementing Enhanced Trench ET-IGBT cell designs, Emitter Switched Thyristor EST structures as shown in ➔ 4 and integration solutions such as the bi-mode insulated-gate transistor (BIGT).

A customized press-pack module (StakPak) was developed for series connection of IGBT and diode chips to be used in grid applications. The mechanical design is optimized to clamp the press packs in long stacks. The module remains fully functional due to its design with individual press-pins for each chip as shown in ➔ 5. Furthermore, the choice of materials is optimized to achieve high reliability.

Today, high-power IGBT press-pack and insulated modules have ratings ranging from 1,700 V / 3,600 A to 6,500 V / 750 A.

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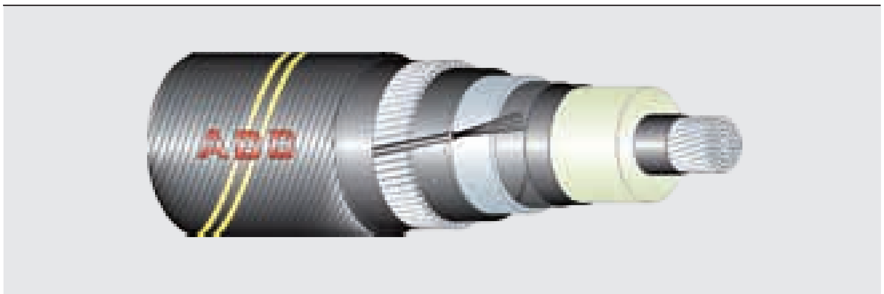
Crossing land and sea

High-voltage DC cables

THOMAS WORZYK, TORBJÖRN SÖRQVIST, OLA HANSSON, MARC JEROENSE – **It is notable that Gotland 1, the very first modern HVDC project of the 1950s, featured an underwater link. Following this 1954 breakthrough, further HVDC cables were installed across the world. ABB has as of today delivered 2,300 km of mass impregnated DC cables.**

1 Laying the Gotland cable in 1954

2 An extruded HVDC cable for submarine application, equipped with optical fibers for temperature monitoring



The Gotland 1 link ➔ 1 did not only feature the first submarine MI (mass-impregnated) HVDC cable, but it also heralded an era of onshore connections. A new link was built at Gotland in 1999 using an 80 kV extruded HVDC cable system. Three years later ABB installed the Murray Link at the antipodes using almost twice the voltage (150 kV) and more than double the length (180 km). The Murray Link is still today the longest land-based high-voltage cable in the world. The contracting of a number of extruded HVDC cable projects for offshore wind farms at ± 320 kV is a clear indication for the confidence in this technology. As of 2015, the energy supply of Lithuania will be supported by the record-breaking NordBalt project. With its 400 km submarine section, NordBalt will be the longest extruded high-voltage cable in the world. Once the DolWin2 cable system is complete, ABB will have installed more than 5,000 km of extruded HVDC cable ➔ 2–3.

The Murray Link is still today the longest land-based high-voltage cable in the world.

Almost all modern HVDC cables are single-core. The simplicity of the design is one of the reasons for the significant reduction in required investment compared with HVAC. HVDC cables can be manufactured in many varieties. Round copper or aluminum conductors of large sizes can be used. There are two different insulation types used for HVDC cables: Mass-impregnated cables (MI) have a layered insulation made of special paper and impregnated with a

HVDC and HVDC cables have always had a flavor of fascination – from the War of Currents between AC and DC at the end of the 19th century to the German “Energiewende,” engineers and even the public continue to discuss the fantastic possibilities of HVDC cables to transport large amounts of power over virtually unlimited distances. During the first half of the 20th century, HVDC research in countries such as Sweden, the United States and Germany focused on converter stations. The development of high-voltage cables principally served the widespread AC technology. Although some of the peculiarities surrounding HVDC cables were understood early on, manufacturing experience remained scarce. An HVDC cable system was built during WW II in Germany but was never commissioned due to the turmoil of war. It was later re-erected in Russia as an experimental line. A submarine HVDC connection between Norway and the Netherlands was proposed as early as 1933, 75 years before ABB realized this link.

ABB’s predecessor cable factory (Liljeholmens AB) performed HVDC tests on mass-impregnated cable in the 1940s, maybe sensing the upcoming interest in the market where grids were expected to grow after the war. At the same time, the work of Dr. Lamm in Ludvika resulted in mercury-arc valves with acceptable reliability.

As so often happens in technical development, not only ingenuity but its combination with pioneering spirit and a certain market situation lead to the breakthrough – and to the Gotland project. The Swedish State Power Board decided in 1951 to connect the Swedish Island of Gotland electrically to the mainland – a distance of 100 km. No other technology but a submarine HVDC cable could solve the task. It was a bold decision – nobody had done this before.

Bjurström, the mastermind of Liljeholmens AB at that time, presented the Gotland cable at the 1954 Cigré conference, in a paper humbly titled “A 100 kV DC cable.” The Gotland cable was a masterpiece of its time, engineered to be reliable. While it is quite easy to produce a few hundred meters of cable, the production and installation of extreme lengths is a very different business. Bjurström and his colleagues put all the best into the Gotland cable:

- Solid 90 mm^2 solid copper conductor in order to reduce disadvantageous conductor expansion under cable torsion in manufacturing or submarine laying
- 7 mm mass-impregnated insulation, comfortably exceeding physical requirements
- Extra-dense insulation paper in order to avoid partial discharges or ionization as it was called at that time
- Double lead sheath. Liljeholmens AB later developed a continuous lead sheathing machine, which improved the quality and emerged as a virtual standard in high-voltage cable sheathing
- Double armoring in the landfall cables

The cable design was so successful that the original Gotland cable link could be upgraded from 100 to 150 kV when power demand increased. A piece of the original cable was analyzed after decommissioning a few decades later and showed no signs of aging.

Today, only the double-lead sheath would be manufactured differently.

high-viscosity compound. The other type, the extruded insulation, comprises a polymeric insulation made by continuous extrusion of ultra-clean polymeric material. MI cables are a good choice for the highest ratings but extruded cables are catching up. Both insulation types are solid, ie, no harmful oil is spilled should the cable be damaged.

Since the insulation must be protected from water, submarine HVDC cables always feature a metallic sheath serving as a water block and path for short-circuit currents. Extruded underground HVDC cables can instead use a lightweight metallic laminate sheath and a copper wire screen.

The HVDC cable can be dressed with tough outer plastic sheaths, or wire armoring for, eg, subsea applications. The extruded HVDC cable can be installed in the most challenging environments, such as the deep sea and vertical shafts ➔ 4.

> The simplicity of the HVDC cable design is one of the reasons for the significant reduction in required investment when compared with HVAC.

Characteristics of HVDC cables

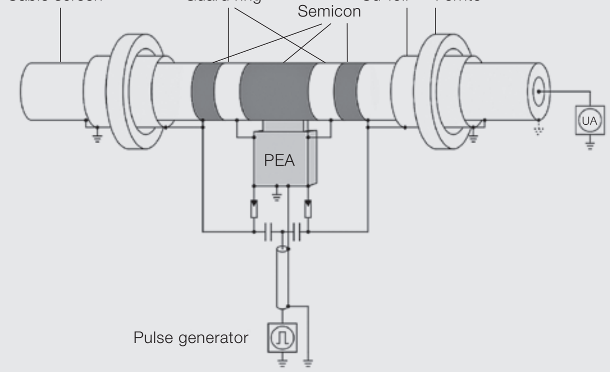
At first sight there is not much difference between an HVAC and an HVDC cable. Both contain a conductor, insulation, a water barrier and in the case of the submarine cable, armor. The main difference lies in the electrical high-voltage insulation.

From an electrical point of view, HVDC insulation behaves differently than its HVAC counterpart. While the electrical field – an important design and operational parameter – is defined by the permittivity in an HVAC cable, it is (also) controlled by the resistivity in the HVDC case. The resistivity of the insulation material depends in part on the temperature. A loaded cable generates heat in the conductor, which will typically result in a temperature drop across the insulation. The temperature distribution will have a corresponding effect on the resistivity distribution. As a result, the electrical field distribution may be inverted in a loaded HVDC cable compared with HVAC (where the electric field is always the highest at the conductor screen and decreases toward the insulation screen). The effect of field inversion is a well-known peculiarity of both mass-impregnated and extruded cable.

4 Selection of ABB's groundbreaking HVDC cable projects

Project name	Location	DC voltage	Insula-tion	Year	Remarks
Gotland 1	Sweden	100 - 150 kV	MI	1954	First submarine HVDC cable ever
Baltic Cable	Sweden-Germany	450 kV	MI	1994	Highest Voltage, longest length at that time
Murray Link	Australia	± 150 kV	XLPE	2002	Longest underground cable system of all times.
NorNed	Norway-Netherlands	± 450 kV	MI	2008	580 km. Longest power cable system, all categories
SouthWest Link	Sweden	± 320 kV	XLPE	2015	First extruded HVDC system with combined cables and OH line.
NordBalt	Sweden-Lithuania	± 300 kV	XLPE	2015	Longest HVDC Light system, 400 km submarine cable route with cost-saving Al conductor

5 The PEA technique presents a reliable method to quantify space charge



The main difference between HVAC and HVDC cable lies in the electrical high-voltage insulation.

The development of the extruded cable took time: The physics of the polymer insulation under DC electric stress was a new area, and proper non-destructive measurement technology was not available. In the 1960s, theorists had predicted that so-called space charges would impact the electric field and therefore possibly have a negative effect on the performance of the cable. Space charges, as the term suggests, are charges that are present inside the insulation. These charges will affect the local field strength and "distort" the distribution of the electrical field. In the 1980s Tatsuo Takada in Japan presented a reliable measurement technology to quantify space charge in both magnitude and space. The measurement principle is called the pulsed electro-acoustic (PEA) method. ABB was one of the first companies to use it → 5.

Applying this tool as well as a wide technology base in physics, chemistry and high-voltage engineering, ABB was able to develop 80 kV extruded cable systems. The technology has since been boosted to 320 kV.

Cable accessories for HVDC Light extruded cables utilize a combination of geometric and refractive field grading for capacitive field distributions and nonlinear resistive field grading for DC field distributions. The accessories are designed to ensure an appropriate electric-field level when subjected to time-varying voltages (such as lightning and switching impulses). DC field control is achieved by a continuous layer of nonlinear field grading material (FGM) connecting full potential to ground.

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Conversion

HVDC valves

JONATAN DANIELSSON, BAOLIANG SHENG – The heart of the converter is the valve, which comes in two basic designs for HVDC Classic and HVDC Light®, based on thyristors and IGBT semiconductors, respectively.

Two different designs of thyristor-based line-commutated valves have been developed by ABB: a conventional base-mounted design with support insulators standing on the floor, and another (more frequently used) design with the valve suspended from the ceiling of the valve hall ➔ 1. The latter design is particularly suitable for withstanding seismic stresses, but also offers cost advantages.

The design uses a modular concept to ensure high reliability while retaining the flexibility to design valves according to customer requirements and preferences. A valve is built up with one or several layers depending on the required voltage withstand capability ➔ 2. Each layer consists of series-connected thyristor modules with intermediate current-limiting reactors, corona shields and piping for the cooling liquid. The individual parts are supported by a mechanical structure with a central shaft running vertically through the structure with ladders and working platforms for easy access.

Thyristor modules

Thyristor modules are of a mechanically standardized compact design.

1 Valve suspended from the ceiling of the valve hall

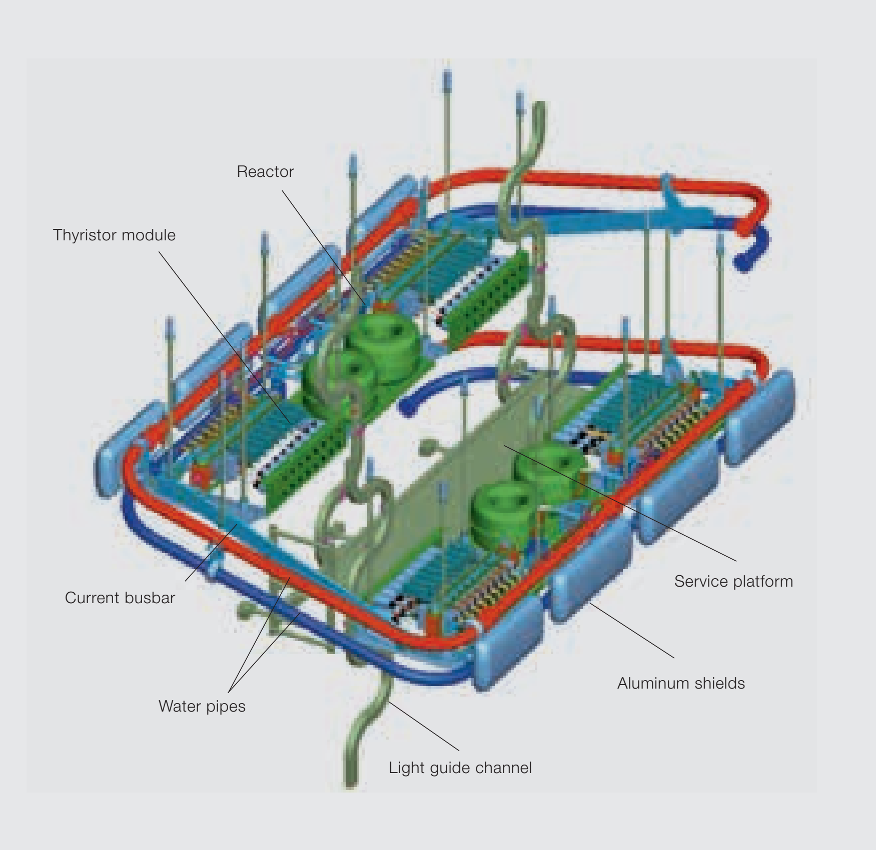
For the sake of reliability they have a minimum of electrical components and connections. The main components are thyristors and their voltage dividers, control units and heat sinks.

> The design uses a modular concept to ensure high reliability while retaining the flexibility to design valves according to customer requirements and preferences.

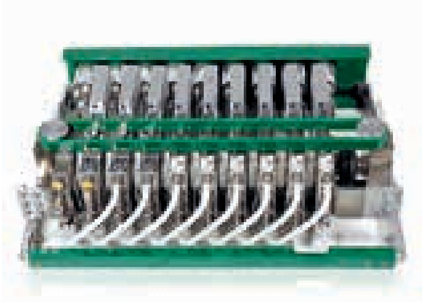
The modules are of compact design for easy access during maintenance. The design allows components to be exchanged without opening the water cooling circuit ➔ 3.

Each module contains a number of thyristors connected in series. Continuous thyristor development enables them to handle ever-increasing voltages and currents, while also reducing conducting and switching losses. The first HVDC valves designed by ABB were for the upgrading of the Gotland transmission – they used thyristors with an area of 5 cm². The next valve design (used for the Skagerrak transmission) featured double-sided cooling of the thyristors, which had an area of 8 cm². Today thyristors have an area of up to 130 cm² capable of withstanding continuous currents up to 4,500 A and short-circuit current up to 50 kA, eg, for the Xiangjiaba-Shanghai ± 800 kV Ultra-HVDC project [1].

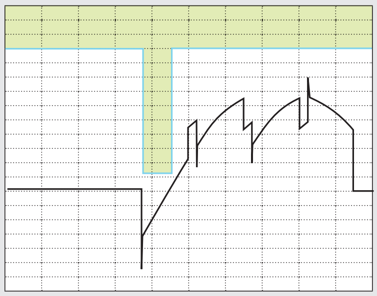
2 Single layer of a valve



3 Thyristor module



4 Voltage across thyristor level



A switching position is built up from a thyristor with two parallel circuits, each consisting of a damping circuit and a DC grading circuit, as well a TCU (thyristor control unit). The TCU converts the optical firing pulses from the control system to electrical signals to trigger the gate that fires the thyristor. The TCU includes state-of-the-art built-in functions that protect it against overvoltages during the reverse recovery period (after a thyristor turns off) as well as from high voltages in the forward blocking state → 4.

By using this hybrid technique, ABB is able to provide a very compact TCU. ABB's service record is also unbreakable: Of the more than 19,000 thyristors installed since 2000, only four thyristor failures have been reported. This demonstrates the superior design of electrically triggered thyristors.

IGBT-based voltage source converter valves

The use of IGBT-based voltage source converters (VSCs) in HVDC power transmission was a breakthrough. Its first application was in a 3 MW HVDC Light test installation in Hällsjön in 1997. Since then, 20 VSC HVDC power transmissions have been installed or are under construction by ABB alone [2].

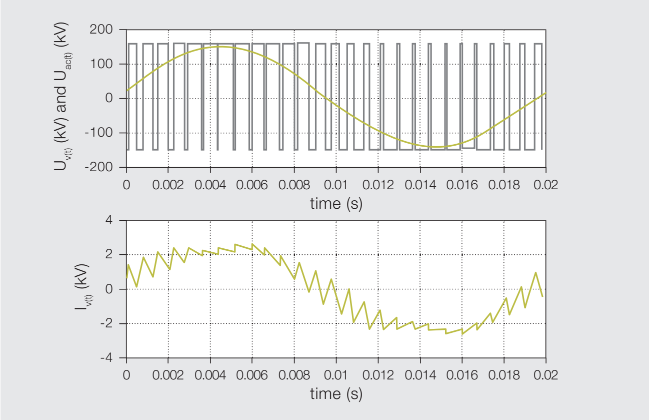
> The liquid in the closed valve cooling system is continuously passed through a deionizing system to keep its conductivity low.

Two types of VSCs have been developed for HVDC transmission: the "switch" type and the cascade two-level (CTL) or "controllable voltage source" type. The choice of converter type mainly depends on the application.

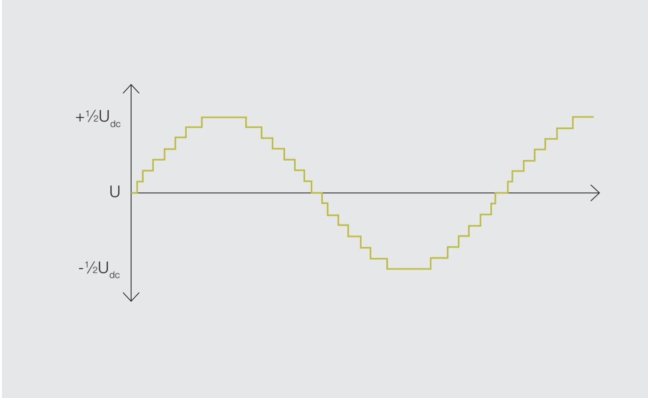
A switch-type valve has a close apparent resemblance to conventional thyristor valves: A large number of series-connected IGBT devices are switched simultaneously. Pulse-width modulation (PWM) is used to achieve a good approximation of a sinusoidal output voltage (AC voltage) → 5.

A CTL converter integrates the DC capacitors into the valve. The valve consists of series-connected voltage cells that can produce a sinusoidal voltage → 6. The greater the number of cells connected in series, the more sinusoidal the waveform. A CTL converter valve for the DolWin1 HVDC transmission project is shown in figure 3 page 25.

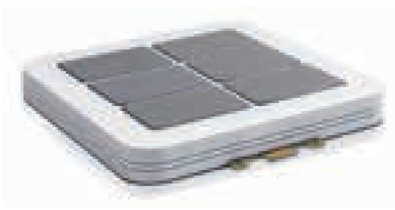
5 Voltage and current in a switch-type VSC valve with PWM



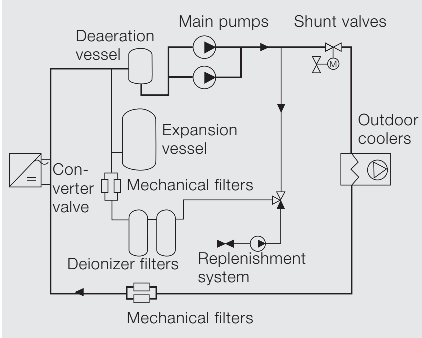
6 Voltage output of a CTL-type converter with seven voltage cells in series connection



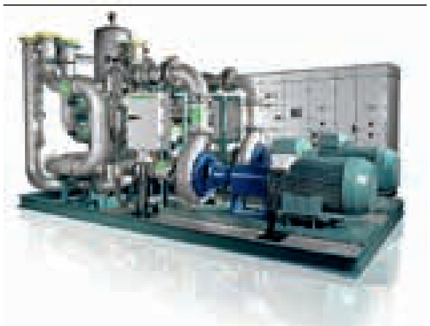
7 StakPak IGBT used in ABB's VSC valves



8 Overview of a typical valve cooling system



9 Typical skid-based modularized redundant cooling system



In this project, one valve consists of thirty-six voltage cells.

The modular design concept for valves is found in both switch and CTL types. ABB's VSC valves use StakPak IGBTs → 7. These switching modules create an internal short circuit should they fail, making them similar to thyristors. This function allows a current to continue to conduct through a faulty IGBT device without calling for an external bypass circuit (as is the case for other IGBT types). The decreased deployment of components at high potential can therefore augment the valve's availability, reliability and compactness. StakPak follows the conventional press-pack design advantages such as better cooling and robust mechanical module structure [3].

Valve cooling

The purpose of the cooling system is to dissipate the power losses generated in the valves. Coolant fluid is circulating through the heat sink in close contact with the semiconductors. This efficiently transports heat away from the device to be cooled through heat exchangers using either air or a secondary circuit. The liquid in the closed-valve cooling system is continuously passed through a de-ionizing system to keep its conductivity low.

A typical valve cooling system is shown in → 8 and → 9.

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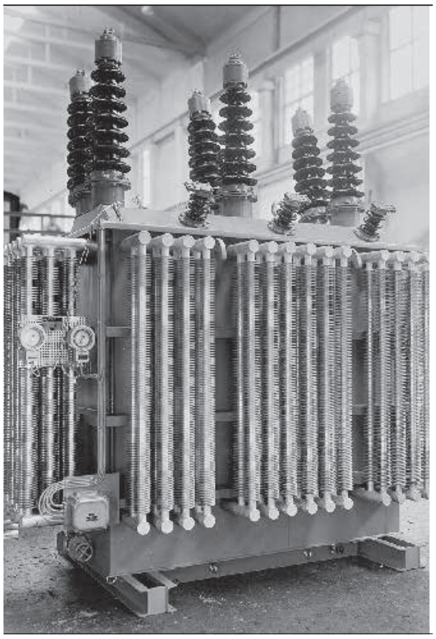
Converter transformers

A 60-year journey

1 An early converter transformer



MATS BERGLUND – ABB's HVDC-transmission transformer technology has evolved from the 1954 Gotland link → 1. ABB's predecessor company, ASEA, broke new ground with its 400 kV DC technology used in the 1,000 MW CU project (Coal Creek Station to Underwood, ND, United States) in 1977. The company asserted its undisputed technology leadership with the Itaipu (Brazil) project of 1982 (3,150 MW / 600 kV DC). This was to be a cornerstone in HVDC converter-transformer history. To realize this record-breaking milestone, ASEA built on the knowledge it accumulated delivering high power transformers to the booming AC-networks during the 1970s.

It was not until the end of the 1990s that anything close to Itaipu would be attempted in terms of transmission power. The next records were set by transmission projects in China: The first two major HVDC links were from the Three Gorges hydropower station to the load centers in eastern China, for which ABB was a key supplier.

A diversification of HVDC-transmission configurations into the Light and Classic variants started at the end of the 1990s. The thyristor-based HVDC Classic has built on its strengths –

2 The function of the HVDC converter transformer

Voltage and dielectric separation
In all HVDC systems (regardless of the converter topology) the HVDC converter transformer serves as an interconnection between the AC grid and the converter valve. Besides converting AC voltage and current to a level suitable for the converter valve, the HVDC converter transformer fulfills additional roles in the HVDC system. For many converter topologies (HVDC Classic and asymmetric HVDC Light®) the most important function of the transformer is to keep the DC-voltage offset created by the converter valve out of the AC network. This results in AC and DC stress being superimposed in the winding of the transformer.

Power and voltage regulation
The HVDC converter transformers is an integral part of the control of the HVDC system, both from an active and reactive power perspective. Compared with other transformers, the HVDC converter transformer often displays a large regulation range – a consequence of its role as an integrated regulating function of the HVDC system.

Short-circuit current limitation and system properties
In the early days of converter valves, a key feature of the transformers was to provide an impedance to limit the short-circuit current to the semiconductor valve. As the capability of semiconductors grew, this property lessened in importance. The transformer still fulfills basic functions in enabling correct interaction between the HVDC transmission and the AC network.

3 Design aspects for the HVDC-converter transformer

High power, high voltage and DC
HVDC converter transformers are among the largest transformers in terms of power, voltage and complexity. On top of this come the requirements dictated by the need to handle DC voltages.

Impact from current harmonics
For some applications, the load current seen by the transformers is not perfectly smooth. This implies extra care for the thermal dimensioning of the HVDC converter transformer as well as its accessories, bushings and tap changers.

Reactive loading
For HVDC transformers, reactive power capability of the complete transmission is translated into the transformer's ability to handle the reactive load.

Short-circuit-like duty
The mercury-arc valves of the early HVDC days sometimes "backfired," subjecting the transformers to a condition close to short circuit. Apparently, the ABB design was sufficiently robust as there is no history of short-circuit incidents – but this was not formally proven until 2007 when ABB short-circuit tested an HVDC converter transformer for the first time.

4 HVDC transformer configurations

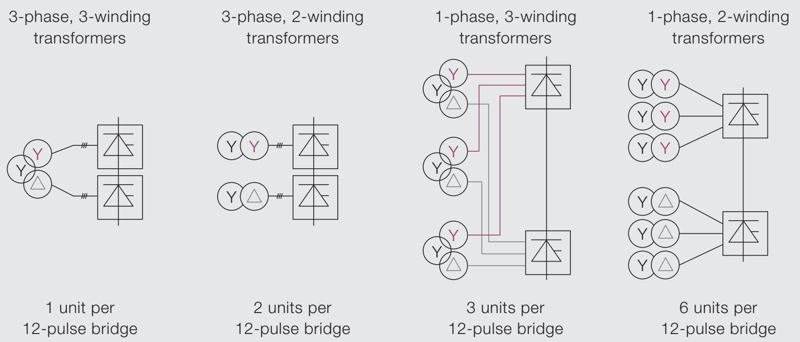
All HVDC systems need transformers, but how these are arranged can vary quite substantially between projects depending on the specification of the project. In their basic forms, each pole of an HVDC Classic system needs to be fed by six phases of transformers while HVDC Light needs a three-phase supply.

The HVDC-transformer configuration of an individual project is unique to the project and determined by the sheer size of transformers in relation to the limitations in the transport infrastructure between the place of manufacture and the HVDC converter station. The main driver behind size of the converter transformer is the rated power, which is a direct consequence of HVDC-transmission power capability and the transformer topology.

For HVDC Classic, the transformer alternatives are shown below.

Typically, more transformers are needed when transmission power and transmission voltage are high. The spare transformers strategy in the converter station also plays an important role in the selection of transformer solution.

For HVDC Light, the transformer solutions possible often are limited to the choice of single-phase and three-phase transformers.



5 Project execution

Technical and scientific proficiency is one important aspect of HVDC converter transformers, but equally important is the way projects are executed and how technology is implemented. HVDC projects often need a long series of HVDC converter transformers being manufactured in a timely manner to complete the supply for an individual project. As lead times for delivery of projects are gradually reduced, this aspect becomes more and more important.

ABB has taken the lead in this important development. The deliveries to SGCC in China are examples where ABB has set industry records. In the project between Hami and Zhengzhou ABB delivered all HVDC converter transformers to the 8,000 MW, 800 kV DC mega-project in 17 months. This should be compared with the delivery times of the Three Gorges projects where the complete time schedule ranged over 36 months. These improvements could very well stem from the abundance of projects delivered: ABB was responsible for more than 50 percent of all the projects realized – far more than any of its competitors.

The ultrahigh DC-transmission voltage is highly challenging to the insulation abilities of the converter transformers.

expanding into ultrahigh transmission voltages enabling very efficient power transmission over long distances. HVDC Light, which started off as a moderate power application, has grown into a medium-power transmission system that nowadays can do what HVDC Classic could do at the end of the 1990s ➔ 2 – 5.

To understand what contemporary HVDC transmission means for the HVDC converter transformers a complete view of the technologies and their applications are given below.

HVDC transformers today

HVDC Classic has in recent years seen rapid expansion in terms of performance. HVDC Classic can now transmit up to 11,000 MW at a transmission voltage of 1,100 kV DC. This means that the transformers must have a very high power rating, and thus a substantial physical size – weighing in excess of 600 t ➔ 6.

The ultrahigh DC-transmission voltage is highly challenging to the insulation abilities of the converter transformers. These are subjected to extreme test voltages before delivery. Besides the voltage stresses often appearing in HVDC Classic, these transformers often claim superlatives in terms of power rating as well. The largest HVDC converter transformers built have single-phase power ratings in excess of 600 MVA – the largest in the world of transformers ➔ 7.

HVDC Light

HVDC Light systems share certain features with HVDC Classic systems, while others are less prominent. Depending on the system configuration, the converter transformers are sometimes exposed to a DC stress similar to that of the HVDC Classic systems, while in some system configurations they are not. The further the capability of HVDC Light advances, the greater the DC stress that the converter transformer must face ➔ 8.

A clear contrast to the HVDC Classic systems is found in the load current that the converter transformers for HVDC Light are subject to. For HVDC Light, the load current is in most cases free from current harmonics, 6 800 kV UHVDC (ultrahigh voltage direct current) converter transformer

8 Converter transformers and the spare transformer at Woodland HVDC Light® station in Ireland.

whereas in HVDC Classic the transformers must cope with the thermal stress originating from the extra losses incurred by current harmonics.

One consequence of the reactive power capability of HVDC Light is that a large portion of the load can be reactive, something that needs to be carefully considered in the transformer design.

The future

It is not only the DC voltage level on the HVDC transmission itself that is being increased. Another trend is that

7 Power rating references

Project	Rated power	Year
Itaipu	314 MVA	1982
Quebec-New England	404 MVA	1987
Sylmar	625 MVA	2007
Rio Madeira	630 MVA	2011
Celilo upgrade	785 MVA	2014

The thyristor-based HVDC Classic has built on its strengths – expanding into ultrahigh transmission voltages enabling very efficient power transmission over long distances.

HVDC converter transformers will need to connect HVDC systems directly to AC networks at even higher voltages than are used today. An HVDC-transformer technology for interconnecting the highest voltage DC transmissions to 800 kV AC systems already exists and there will soon be commercial applications. Beyond this, interconnections to even higher AC voltages, such as the 1,000 kV AC networks in China, are a possibility.

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Capacitors

A key component in HVDC systems

BIRGER DRUGGE, PETER HOLMBERG – Capacitors have multiple functions in HVDC systems ➔ 1. They cover aspects such as reactive power compensation, DC filtering, AC filtering and power-line carrier coupling. Capacitor technology for HVDC has gone through the various shifts in technology from impregnated mixed dielectrics (paper/film) to full-film dielectrics with highly specialized capacitor fluids. The latest technology used in HVDC Light® applications features dry solutions based on special metallized film dielectrics.

1 Capacitor bank at Porto Velho HVDC station in Brazil

ABB's technology is based on its long experience and deep understanding of specific DC phenomena such as space charges. An example of ABB's prowess is the internally fused capacitor used to maintain high levels of power quality and availability.

HVDC's increasing voltage levels have introduced special mechanical challenges in the design of the capacitor stacks, not the least of which concern seismic requirements.

Capacitors are part of the output filter that reduces harmonics. One challenge faced is that these harmonics generate sound in the components. Special patented sound-attenuating solutions have been developed to keep the sound level low and meet environmental requirements.

As a technology leader, ABB also drove the technology shift to dry HVDC capacitors for HVDC Light, required to handle unit voltage ratings above 150 kV. ABB's dry DC capacitor technology is based on metallized film with self-healing properties. With ABB's dry technology, customers benefit from higher availability and reduced footprint of the link, also improving the eco-aspect of the solution.

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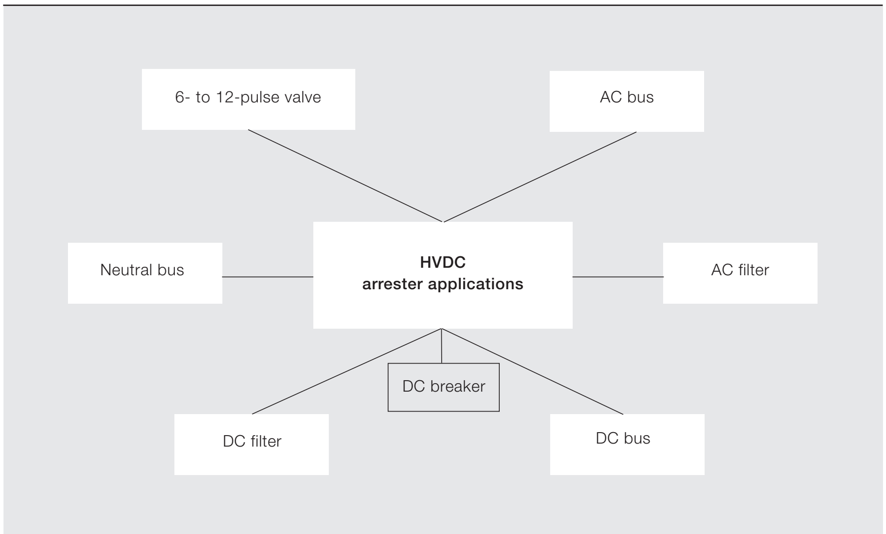
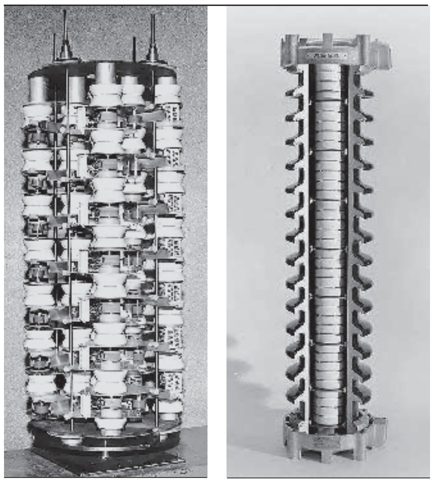
1 ABB's HVDC arresters



2 Comparison of gapped SiC arrester and gapless ZnO surge arrester



2a XDL 280 A surge arrester (1970s)

2b ZnO surge arrester (1980s)

Surge arresters

60 years of HVDC protection

LENNART O. STENSTROM, JAN-ERIK SJÖDIN – An HVDC station features different types of surge arresters to protect the equipment from overvoltages caused by lightning and/or switching events. In some equipment such as DC breakers, surge arresters also may form an integral part of the apparatus.

The stresses the arresters have to be designed for, compared with normal AC arresters, are characterized by, for example:
– Special voltage waveforms comprising frequency components ranging from pure DC, and power frequency to several kHz
– Very low protection levels required
– High energy demands – eg, for valve arrester, neutral-bus arresters and arresters for DC breakers
– High ambient temperature, eg, for valve arresters

The various arresters normally used in an HVDC project are shown in → 1.

Historically HVDC stations were first protected by gapped SiC surge arresters until the late 1970s when gapless ZnO surge arresters were introduced. The last generation of the gapped arresters were quite complex and comprised a vast number of components such as spark gaps, SiC blocks, grading capacitors and grading SiC resistors. The design became even more complex when parallel columns had to be used to meet high energy demands or low protection levels → 2 shows how the introduction of the ZnO material remarkably simplified the internal design of the surge arresters compared with the previous gapped HVDC arrester.

A short history of ABB (and predecessor company ASEA) HVDC surge arresters is shown in → 3 and → 5.

ABB has a number of designs for HVDC arresters optimized for thermal, electrical and mechanical stresses, safety requirements and cost depending on the application.

To date, tens of thousands of ABB HVDC arresters have been delivered worldwide with an excellent service record.

Instrument transformers – reliable metering and protection

ABB has been producing instrument transformers by the thousands for more than 70 years → 4. Their applications range from revenue metering, control, indication and relay protection. One field of application in HVDC is the use of capacitor voltage

3 Surge arrester history at ABB

Pre-1979: Gapped SiC arrester
1979: First gapless ZnO surge arrester (probably the world's first) delivered to a 250 kV HVDC station in Denmark ➔ 5a
2000: First 500 kV arrester with polymer-housing delivered to the 3GS project in China ➔ 5b
2006: First 800 kV arrester type tested and energized for a China project
2012: First 1,100 kV arrester fully type tested ➔ 5c

4 420 kV cap. volt. transf.

5 The first gapless HVDC arrester and the first 500 and 1,100 kV DC bus arresters with polymer housings

5a Gapless HVDC line arrester (1979)

5b 500 kV DC bus arrester (2000)

5c 1,100 kV DC bus arrester (2012)

ABB has been producing instrument transformers by the thousands for more than 70 years.

transformers to obtain the source voltage for converter control, as well as to obtain signals for the protection of the converter station. The output from the capacitor voltage transformers is used to trigger the thyristor valves at a certain time, based on the previous zero crossing of the AC voltage. Because even minor disturbances can be disastrous to the operation of the HVDC station, special requirements must be met for transient and frequency response.

The first capacitor voltage transformers were produced by ABB in the 1950s for delivery to the 1,000 km, 400 kV AC transmission line from Harsprånget to Hallsberg in Sweden. The electromagnetic unit in the base of a capacitor voltage transformer incorporates an inductive reactor, connected in series between the capacitive voltage divider and the high-voltage end of the primary winding, to compensate for the shift in phase angle caused by the capacitive reactance of the capacitor's voltage divider. This type of compensation allows simple construction to obtain high accuracy for high loads. However, the reactance and capacitance form a tuned circuit that gives relatively low accuracy at frequencies outside the nominal frequency.

In an HVDC application, the capacitor voltage transformer that is used to obtain the source voltage for special requirements in converter control for transient and frequency response uses an electromagnetic unit without a separate compensation reactor. For this special type, the function of the compensation reactor and the primary winding of the intermediate transformer are combined into one device. This arrangement gives a substantially increased operating frequency range, and highly improved transient response.

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Trend lines

The first high-voltage direct current (HVDC) pioneers started work in the early 1920s, but it was not until 1954 that ASEA, a predecessor of ABB, was able to develop and commission the first commercial subsea HVDC link, to the island of Gotland, in Sweden. Since then, HVDC technology has been characterized by rapid and continuous advances driven by new and demanding customer needs. Despite the maturity of the technology, the last few years have seen a steady stream of world-record-breaking achievements in both the classic line-commutated converter (LCC) and in the more recent voltage source converter (VSC) areas. HVDC progress has, to a large extent, been made possible by the evolution of a particular set of key technologies and products and it is likely that these will continue to drive the field for the foreseeable future.

Future directions in HVDC transmission

Technologies for bulk power transmission are evolving fast

1 HVDC is the technology of choice for bringing distant offshore wind power to shore.

PER SKYTT – Advances in HVDC technology in recent years have been breathtaking: Bulk transmission for extremely long distances has reached levels of 8 GW using ± 800 kV ultrahigh-voltage DC and ratings above 10 GW are envisioned within a few years; world-record subsea transmission cable projects have opened the door to the further expansion of the global power cable network; and new VSC technology will simplify the job of connecting weak AC networks as well as making it easier to transfer power from offshore wind generators and other remote renewables → 1.

In addition, HVDC makes it more straightforward to interconnect asynchronous AC networks and it can effectively be used in very long subsea cables that connect AC systems. HVDC is also ideal for powering offshore oil and gas installations with clean electricity from shore. Further, embedding HVDC in AC systems is an effective way to reinforce bulk transfer and strengthen the AC system operation.

Customer values

As in many technology areas, one of the most important aspects of the product is a continuous reduction of cost for the user during its entire life cycle – which in HVDC can span decades. The initial investment, driven by equipment and plant size, and engineering and commissioning efforts, can be considerable and improved technology and processes can contribute significantly to cost reduction here. HVDC also saves cost during operation because total electrical system losses, a major factor for many operators, are lower than in other solutions.

Other aspects are important too: As HVDC is a part of critical national electrical infrastructure, reliability and

2 HVDC lines in Brazil. HVDC meets many criteria for bulk electrical power transport.

3 Evolution of HVDC Classic power and voltage ratings

Valve type	Year	Voltage (kV)	Power (MW)
Mercury arc	1954	100	20
Mercury arc	1968	533	1,440
Thyristor	1970	50	10
Thyristor	1977	250	500
Thyristor	1978	500	560
Thyristor	1979	400	1,000
Thyristor	1985	500	2,000
Thyristor	1987	600	3,150
Thyristor	2003	500	3,000
Thyristor	2010	800	6,400
Thyristor	2013	800	7,200
Thyristor	2014	1,100	10,000

availability become essential considerations. In addition, less-easily definable requirements often come into play, such as an efficient approval process for the system, the supplier's experience, simplicity of updates and upgrades, and project execution time ➔ 2.

Performance improvements

Even though HVDC technology has reached a point at which many vital and demanding applications can be satisfied, there is a need for further enhancement in capabilities and performance:

- Increased power ratings and lower losses for bulk transfer using LCCs
- Increased power ratings for VSCs – enabling connections to remote renewable generators or the interconnection of weak AC networks
- Further reduction in HVDC station size – allowing applications offshore and in constrained urban areas

These enhancements will come about by developments in key enabling-technology areas ➔ 3.

Enabling technologies

The advances in HVDC have, to a large extent, been made possible by the evolution of a particular set of key technologies and products. These same technologies and products provide the arena in which future decisive steps will be taken. The improvements being made to individual components and the way they are used within HVDC systems suggest that HVDC transmission systems will continue to gain in functionality and capacity for the foreseeable future.

Breaking DC currents has been a major challenge when applying HVDC on a large scale. However, ABB's new hybrid HVDC breaker has changed this.

Power semiconductors

The core of an HVDC system is a silicon-based power semiconductor device: a thyristor in an HVDC Classic system, or a more controllable transistor device, an IGBT (insulated-gate bipolar transistor), for HVDC Light ➔ 4–5. This technology benefits from the astonishing progress that has been made in the mainstream semiconductor business – where fabrication processes for microprocessors and computer memory have pushed material and processing limits beyond what many thought possible. The industry has gone from 4-inch to 5-inch and now 6-inch thyristors, increasing current ratings. Voltage ratings have been increased by many kilovolts purely with enhanced processing ability and material quality. The IGBT has seen an even more drastic development in the past few years that has enabled VSC HVDC to reach the 1 GW level. This development looks set to continue for many years to come, until silicon-based technology reaches its theoretical limits. Already, however, other even more capable semiconductor materials, principally silicon carbide, are emerging as the basis of new components. Indeed, silicon carbide devices have already started to appear in lower power applications.

Insulation

The DC voltage withstand of HVDC components and systems is a critical factor to consider when designing reliable and compact electrical systems. DC voltage withstand limits have been pushed ever higher in recent years and systems operating at 1,100 kV have recently been made possible. But better DC voltage

4 Assembly of thyristors at ABB's semiconductors facility

5 ABB StakPak with four and six submodules

withstand has advantages other than higher operating voltages and capacities – converter stations can be made smaller, for example. Gas-insulated solutions for DC will play a major role as will further expansion of the air-insulated switchgear design envelope.

Cable technology

A key enabling product for HVDC is the lightweight polymer-insulated cable, which allows systems with higher transmission capabilities to be built. Recent history shows a dramatic evolution of the cross-linked polyethylene (XLPE) DC cable, for instance. The first HVDC Light systems operated with a system voltage of 80 kV and projects currently under construction will operate at ± 320 kV, enabling 900 MW of power to be transmitted. And there is scope to expand cable development much further: Theoretical limits are well above current ratings and this points to the possibility of future cables performing at levels far above current ones.

The DC voltage withstand of HVDC components and systems is a critical factor to consider when designing reliable and compact electrical systems.

DC breakers

Breaking DC currents has, for many years, been seen as a major challenge when applying HVDC on a large scale. However, ABB's new hybrid HVDC breaker has changed this and has thus ushered in a new era of HVDC transmission networks. This paves the way for large multiterminal systems and a future supergrid HVDC system that will be superimposed on the existing AC network.

Control systems

An HVDC system comprises a collection of controllable equipment that needs constant monitoring and control. The semiconductor valve itself, for example, relies on a very fast and reliable automatic control regime to fire the thyristors in the HVDC Classic product, or to fire the on and off signals for the IGBTs in HVDC Light. Apart from this, the entire electrical and auxiliary systems need to be constantly monitored and controlled to ensure all components work in harmony. ABB has developed such dedicated control and protection systems – starting with ones based on vacuum tubes that then evolved into relay-based solutions. The latest systems use, as their basis, advanced electronics that are tailored for HVDC.

Trends

From day one, pioneering technology has ensured ABB's leading position in the HVDC field. This leadership will be of great importance in the planning of future electrical transmission systems – in which HVDC will play a major role. In addition, the theoretical limits of HVDC's core technologies have not yet been reached, so HVDC holds great potential and is set to become an even more dominant technology for bulk power transmission.

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Breaking step

ABB's unique hybrid HVDC breaker is a key component for future grids

1 ABB's new hybrid HVDC breaker will revolutionize the HVDC field by making multiterminal HVDC grids possible.

JÜRGEN HÄFNER, REZA DERAKHSHANFAR, PETER LUNDBERG – The best way to transport large quantities of electrical power over long distances with minimal losses is to use high-voltage direct current (HVDC) technology. Because more, and more remote, renewable power sources are coming online and urban centers of consumption are pulling in power from further and further afield, the importance of HVDC is growing rapidly. However, since the dawn of HVDC technology, almost a century ago, one major com-ponent has been missing – a low-loss breaker that is appropriate for the high voltages and high speeds required. The absence of this critical component has confined HVDC topology to point-to-point configurations; an HVDC grid has remained infeasible. All this has changed with the launch of ABB's new hybrid HVDC breaker.

The many HVDC transmission lines scattered around the globe have one thing in common: They are all point-to-point connections. There is no HVDC grid. The reason for this has been the absence of a breaker that could handle the high voltages and high response speeds involved, and that could operate within acceptable loss limits.

This 100-year-old electrical engineering problem has now been solved by the introduction of ABB's new hybrid HVDC breaker → 1.

The hybrid HVDC breaker melds reliable power electronics already used in HVDC converter stations and fast-disconnecting gas-insulated switchgear technology to fill a gap in the products needed to build large multiterminal systems with multiple protection zones.

The hybrid HVDC breaker opens up a new era not only for the transport of renewable energy but also for all other types of generated power that has to be transmitted over long distances, including under large bodies of water. Further, the ability to create HVDC grids will improve overall grid reliability and enhance the capability of existing AC networks.

> This 100-year-old electrical engineering problem has now been solved by the introduction of ABB's new hybrid HVDC breaker.

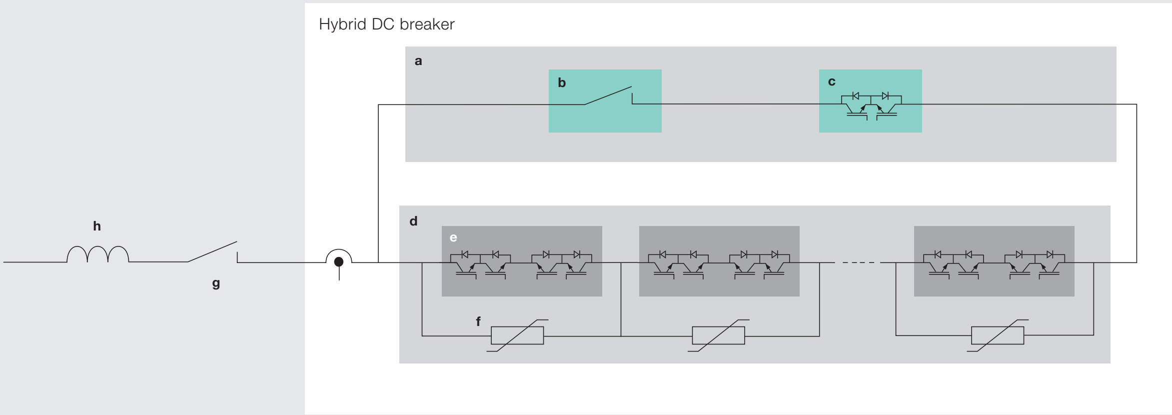
Technical background and system requirements

Until now, protecting a multiterminal HVDC grid in the event of a fault would demand a coordinated operation by all the terminals to abort the active power flow in the entire multiterminal system.

Building multiterminal HVDC systems with more than one protection zone would increase the robustness of the system during DC faults and would be of great value to the customer. However, the absence of a suitable breaker has, until now, limited the feasibility of this.

DC breakers are required to protect voltage source converters from line faults in DC grids and to enable a reactive power compensation mode for voltage stabilization in point-to-point and multiterminal HVDC applications. The relatively low impedance of HVDC systems presents a challenge when short-circuit faults occur in a DC link because the fault penetration is faster and deeper compared with the AC equivalent. Consequently, ultrafast HVDC breakers are needed to isolate faults and avoid a collapse of the common HVDC grid voltage. In DC systems, fault currents grow steadily in one direction. The lack of (naturally occurring) zero crossings and the response speed requirements have long been the main challenges [1].

2 Hybrid IGBT DC breaker



a Main current branch (when current is flowing) consisting of:
b Ultrafast disconnector
c Load-commutation switch (semiconductor-based)

d Main HVDC breaker consisting of:
e Semiconductor interrupter
f Arrester bank

g Residual current breaker
h Current limiting reactor

3 The ultrafast disconnector

DC breakers should have negligible transmission losses and be easy to integrate into a converter station design. Mechanical breakers have very low losses, but developing a very fast mechanical HVDC breaker is a challenge. Semiconductor-based HVDC breakers, on the other hand, easily surmount the limitations of switching speed and voltage, but generate high transfer losses.

ABB's hybrid HVDC breaker system [2] overcomes these hurdles with a combination of mechanical and semiconductor devices. It has an opening time of less than 5 ms, a few tens of kilowatts of on-state losses and a size that increases the footprint of an HVDC converter station by only 5 percent. This breaker is a milestone in the history of electrical transmission and solves a central problem of HVDC grids.

How it works

The hybrid HVDC breaker consists of a main breaker branch made up of semiconductor switches and a bypass branch composed of a semiconductor-based load-commutation switch (LCS) in series with a mechanical ultrafast disconnector (UFD) → 2.

The main breaker path is separated into several sections with individual arrester banks that are dimensioned for full voltage- and current-breaking capability. The LCS is dimensioned for a lower voltage and energy capability. After fault clearance, a disconnecting circuit breaker interrupts the residual current and isolates the faulty line from the HVDC system in order to protect the arrester banks from thermal overload.

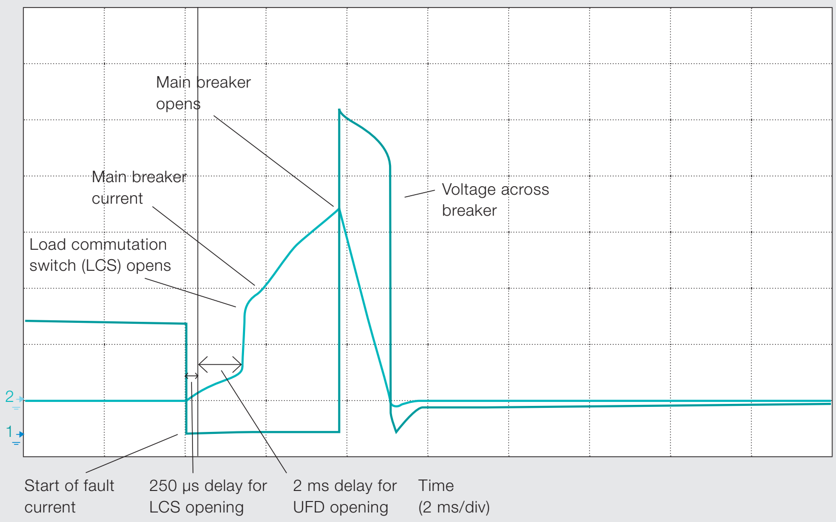
Each main breaker section contains semiconductor stacks composed of series-connected insulated-gate bipolar transistor (IGBT) DC breakers. Due to the large di/dt stress during current breaking, a mechanical design with low stray inductance has been adopted. Application of ABB StakPak IGBTs enables a compact stack design and ensures a stable short-circuit failure mode in case of component failure. Individual resistor-capacitor-diode (RCD) snubbers across each IGBT module ensure equal voltage distribution during current breaking. Optically powered gate units enable operation of the hybrid HVDC breaker independent of current and voltage conditions in the HVDC system.

A cooling system is not required for the main breaker, as the semiconductors are not exposed to the line current during normal operation – then, the current will only flow through the bypass. The LCS opens proactively at a certain fault current level in order to commutate the fault current, almost instantaneously, into the main breaker. Thereafter, the UFD opens in less than 2 ms to disconnect the load commutation switch from the main breaker. After the UFD is opened, the main circuit breaker is ready for operation.

One IGBT for each current direction is sufficient for the LCS to fulfill the requirements of the voltage rating. The transfer losses of the hybrid HVDC breaker are thus significantly reduced – to less than 0.01 percent of transmitted power. Parallel connection of IGBT modules increases the rated current of the hybrid HVDC breaker; series-connected, redundant IGBT positions improve the LCS reliability. A three-by-three matrix of IGBT positions for each current direction was, therefore, chosen

The hybrid HVDC breaker melds reliable power electronics already used in HVDC converter stations and fast-disconnecting gas-insulated switchgear technology.

4 Hybrid HVDC breaker test results showing fault current and voltage versus time



for the base design. A minor cooling system is required due to the switch's continuous exposure to the line current.

The UFD opens at zero current with low-voltage stress and can, thus, be realized as a disconnector with a lightweight and segmented contact system ➔ 3.

System validation and key component testing

Successful verification testing at device and component level has proven that the system performs as required. The complete hybrid HVDC breaker has been verified in a demonstrator setup at ABB facilities. The diagram in ➔ 4 shows a breaking event with peak current of 8.5 kA and a 2 ms delay time for opening the UFD in the branch parallel to the main breaker. Switching performance of the UFD has been verified for 2,000 consecutive open and close operations, including subsequent dielectric integrity tests. Other synthetic tests typical for high-voltage circuit breakers have been performed, verifying the required performance at full ratings. The maximum rated fault current of 8.5 kA is the limit for the generation of semiconductors used during initial testing. Application of bimode insulated-gate transistor (BiGT) devices allows for breaking currents exceeding 16 kA [3].

The purpose of the tests was to verify the switching performance of the power electronic parts and the opening speed of the mechanical UFD. The test object consisted of one 80 kV unidirectional main breaker cell. The higher voltage rating is accomplished by the series connection of several main breaker cells. A similar series connection approach is also used to test HVDC Light and Classic valves. To verify reliable and safe operation, tests have also been carried out with IGBTs that have deliberately been made defective [4].

Benefits, markets and applications

Fast, reliable and nearly zero-loss HVDC breakers and current limiters based on the hybrid HVDC breaker concept have been verified at component and system levels for HVDC voltages up to 320 kV and rated currents of 2 kA. The next step is to test such breakers in a real HVDC transmission line. An increase of voltage rating to accommodate 500 kV HVDC systems by improving UFD insulation extends the range of possible applications of the hybrid HVDC breaker from cable-based DC grids to embedded HVDC links utilizing overhead lines.

The hybrid DC breaker is the key technical element that finally makes a true multiterminal DC grid with multiple protection zones possible. In the extension of existing point-to-point systems and in the construction of new HVDC grids will be where the hybrid DC breaker will be premiered. The hybrid DC breaker will finally allow the long-held visions of HVDC grids spanning Europe and other regions to become a reality.

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Fast and reliable

The MACH™ control and protection system for HVDC

HANS BJORKLUND – High-voltage direct current (HVDC) transmissions have always differed from alternating current (AC) transmissions in that the conduction pattern of an HVDC converter is fully controllable. Indeed, this property is what provides many of the outstanding features of HVDC transmission. To make sure that the HVDC valve conduction sequence is tightly adhered to and that the system is run within the foreseen operating envelope, a fast and reliable control and protection system is required. And the better this system is, the better the HVDC transmission will operate. For this reason, ABB's HVDC control and protection products have always been very quick to exploit the very latest and best technology. In fact, the story of HVDC control and protection systems over the past 60 years mirrors that of the main trends in computing technology.

The modern era of HVDC transmission began in 1954 when the island of Gotland was linked to the Swedish mainland by an HVDC connector. At that time, AC systems still relied on electromechanical relays for protection and control, but the nature of HVDC demanded that the Gotland HVDC link have a very different and much faster system. The best technology available was used: amplifiers based on vacuum tubes – technology unheard of in other areas of power systems at that time → 1. The vacuum tubes were replaced by transistors as soon as they became available in the late 1950s, which greatly increased reliability.

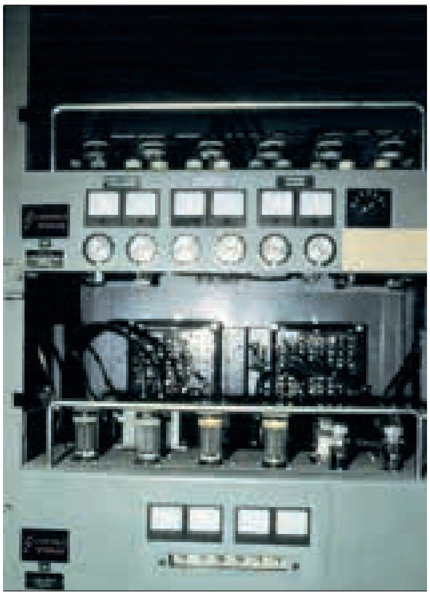
The need for ever faster and higher-precision control systems for HVDC meant that ABB always adopted the latest and most advanced electronic technologies as soon as they became available.

Microprocessors

In the 1970s, the microprocessor was introduced and ABB immediately (in 1973) adopted the Intel 8008 in thyristor monitoring systems. In 1975, the brand-new Intel 8080 was used in ABB's emergency power control system.

The advent of microprocessors finally made it possible to build single board computer (SBC) systems that had everything needed for one function (inputs, A/D converters, microprocessor and output circuitry) on one board. HVDC protection is very different from AC protection in that it has to be much faster (sub-millisecond response) and has to mix DC and AC current and voltage measurements.

1 Original Gotland converter firing control system based on vacuum tubes



An HVDC control system can benefit from a calculation capacity higher than an SBC can provide, so from the early 1980s, solutions that employed parallel-bus backplanes hosting multiple processing boards began to appear. It was fully digital-converter firing control running on multiprocessors that made the world's first fully redundant control system possible in Gotland 2 in 1983.

The need for ever faster and higher-precision control systems for HVDC meant that ABB always adopted the latest and most advanced electronic technologies as soon as they became available.

SBCs are ideal for this. A 16-bit SBC that could implement all HVDC station protection functions by just using different software, was introduced in 1983 for the Gotland 2 transmission link. A few years later, the SBC found large-scale use in the Itaipu project in Brazil, where several hundred were used to implement all protection functions in the HVDC converters.

DSP and FPGA

In the 1990s, two new technologies appeared: the digital signal processor (DSP), with an instruction set tailored for very fast calculations (allowing control system cycle times below 100 µs) and the field programmable gate array (FPGA), which opened up the possibility of implementing larger-scale programmable logic in HVDC applications.

Combining circuit boards using these technologies with the latest 32-bit micro-processors on a fast parallel multiprocessor backplane resulted in

2 PS700, the latest main computer for MACH

3 Distributed I/O unit

the first-generation ABB MACH™ (modular advanced control for HVDC) control system, which was introduced in 1991. The first installation using the MACH system, a cable between Norway and Denmark, was put into commercial operation in late 1993.

PCI bus

When the high-speed PCI (peripheral component interconnect) bus was introduced, it allowed even faster microprocessors to be used, thus further improving the performance of the control and protection system. The PCI bus also allowed ABB to take advantage of DSP computing muscle and introduce, for the first time in the industry, floating-point DSP clusters. When ABB introduced the second generation of the MACH system in 1999, these powerful control and protection computers were combined with a revolutionary input/output (I/O) system that was connected only by serial buses, even for the highest speed measurement signals. This was the first time a control and protection system for a power system application had been built using solely serial buses for all I/O needs (voltage and current measurement, breaker trip and close operations, etc.). This resulted in an extremely flexible control and protection architecture in which the location of the different components could be chosen much more freely than in a conventional system where all signals have to be brought to the various controllers and protection devices by discrete wiring.

PCI Express bus

The use of parallel backplane buses involves many signals and complex connector arrangements. This can introduce unreliability when data transfer speeds increase. Therefore, the industry is moving to multiple serial buses and the PCI bus has now been replaced by the software-compatible PCI Express bus. ABB has used this opportunity to upgrade the MACH system, after 20 years, with a new 64-bit multicore microprocessor unit and new multicore DSP units, all connected by the PCI Express bus. This latest advance means that a control system can be built much smaller, yet with 10 to 100 times the calculation capacity ➔ 2. Further, less power is used, so fans are not necessary – thus increasing reliability. There is backwards software compatibility so that applications developed for earlier systems using ABB's function block programming language, HiDraw, can be recompiled and run in the newest systems.

I/O units

The full assortment of well-proven modular MACH I/O units is still available, but, with the latest MACH generation, ABB is also introducing a series of environmentally hardened I/O units ➔ 3. These can be distributed further afield and placed, for example, in breaker junction boxes or transformers. In this way, the traditional copper cabling connecting the devices back to the control system is replaced by optical fibers.

Computer processing power will continue to increase in the years to come and this will bring further improvements in the capabilities of control and protection systems, and deliver many new and fascinating applications.

The interfaces used in the MACH system have been chosen very carefully so that MACH can continue to evolve and remain the base for ABB's HVDC control and protection systems at least for the next 30 years. Maybe it will even live to see the Gotland HVDC link celebrate its centenary in 2054.

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HVDC grid simulation

A new HVDC grid simulation center brings deeper understanding of multiterminal HVDC control and protection

TOMAS LARSSON, MAGNUS CALLAVIK – It is predicted that the coming years will see an increase in the use of electricity generated by sources remote from load centers and increased integration of electricity markets. High-voltage direct current (HVDC) technology is emerging from being a relatively specialized technology to becoming a central element of the future transmission assets necessary to make this happen in a timely and efficient way. A supergrid or overlay grid based on HVDC is considered to be feasible and also to be the most efficient technology to use for a future extended high-voltage electric network. However, the development will come in steps. As the first building blocks of an HVDC grid are being planned now, there is already a demand for systems for control and protection of converters, lines and DC/AC grid interconnectivity. To advance understanding in this field, ABB has constructed a real-time HVDC grid simulator with control and protection hardware- and software-in-the-loop.

1 Working with hardware in the HVDC grid simulation center

New transmission assets are being planned and constructed to connect power markets and to bring power from remote renewable generators into load centers. HVDC, being the superior technology for transportation of bulk power over long distances, is becoming a major player in this new transmission infrastructure. In the long term, a supergrid or overlay grid based on HVDC is considered to be a very feasible proposition [1]. It makes sense to integrate individual HVDC lines on the DC side of a converter into a grid when the HVDC density in the transmission network increases. Recent developments in voltage source converters (VSCs), cable technologies and DC breakers mean that the time has arrived to plan for such scenarios.

In order to master HVDC grids and to ensure everything is handled in a safe and efficient manner, the behavior, control and protection of converters, lines and DC/AC grid interconnectivity must be understood in a fundamental way. To advance this understanding, ABB has constructed a real-time HVDC grid simulator with control and protection hardware- and software-in-the-loop [2] → 1.

ABB HVDC grid simulation center

The HVDC grid simulation center is a state-of-the-art installation where ABB's ability to meet market requirements and handle the challenges thrown down by DC grids are demonstrated. It forms part of ABB's HVDC response to the growing number of renewable energy sources coming onto the grid, to integration of electric power markets and to the growing problem of power system bottlenecks becoming more frequent as power systems are run closer to their thermal and electrical stability limits.

Further, since the versatility, reliability and availability of a DC grid will help a customer to create a business case, the simulation center provides a forum where practical demonstrations that underline these advantages can take place – for example, by showing the capabilities of a hybrid DC breaker.

A visitor to the ABB HVDC grid simulation center will initially encounter the simulated environment of an operator that represents ABB's proposal as to what an operator would face in his daily work → 2. The operator's computers collate and display information from the simulated power system and transmit orders from the operator to a real HVDC MACH™ control system. All parts of the control system in the HVDC grid simulation center are identical to their counterparts in real-life installations, so everything is operated in real

Since the versatility, reliability and availability of a DC grid will help a customer to create a business case, the simulation center provides a forum where practical demonstrations that underline these advantages can take place.

2 HVDC grid simulation center: a visitor's view

time and the operator experiences exactly the same as he would in a real control room.

Responses from the process – ie, the HVDC converters and the AC and DC power systems – are also obtained in real time, but with one significant difference to a field installation: In the simulation center they are simulated by a model running in a real-time digital simulator (RTDS). For the MACH control system, then, it is a real-world experience, but with one major advantage: Because the high-voltage equipment is simulated, it can be stressed with contingencies, faults and other exceptions that, in some cases, would be totally impossible to perform in a real field installation. This allows verification of responses from troublesome cases that are run in offline simulations. This is of great interest for time-critical processes, such as when a fault in the DC grid is combined with requirements for robust selective tripping involving fast-rising fault currents. By having the real control system in the loop, confidence is gained that the protection in real life will secure the DC grid by fast-tripping only parts that belong to the faulty zone while keeping the healthy circuitry on line.

To advance this understanding, ABB has constructed a real-time HVDC grid simulator with control and protection hardware- and software-in-the-loop.

For an HVDC grid, ABB's philosophy involves overlaying a master controller in order to optimize system disposition. This functionality too has been implemented in the HVDC grid simulation center. Besides assisting the operator in finding an optimal operation point of the DC grid, the master controller also helps to restore the DC grid after a fault. A typical case would be a DC fault in a cable attached to a converter that is acting as a DC voltage controller. The protection system would, after the fault, first clear the fault by disconnecting the cable. The isolated converter could then stay connected on the AC side and, if required, work as a Statcom, eg, SVC Light, providing reactive power compensation. The rest of the system will be intact after the fault clearance but for a short while, given that the DC voltage controlling station tripped, be without a common DC voltage control. In the interim, every converter has its own local functionality to control the DC voltage until the master controller has assigned a new DC voltage controlling station and calculated new optimal set points for the remaining stations.

Apart from demonstrating ABB's performance and ideas in the context of a DC grid, another task of the ABB HVDC grid simulation center is to deliver results to ongoing ABB-internal research and development projects – for example, applications of the DC breaker in a power system.

As the spread of HVDC grids widens in future years, the ABB HVDC grid simulation center will continue to increase in sophistication and scope, and continue to provide insight into HVDC protection and control for ABB and customers alike.

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Gas-insulated HVDC switch-gear

Flexible and compact power routing

1 Examples of DC GIS components

1a DC GIS surge arrester

1b Gas-insulated disconnector and earthing switch

PER SKARBY – Gas-insulated switchgear (GIS) is much more compact and requires far less clearance than air-insulated switch-gear (AIS). Another advantage is the routing flexibility of the ducts compared with cables. GIS is now replicating its AC success in the world of HVDC.

DC GIS has two principal advan-tages: Installa-tions can be made far more compact than the air-insulated switchgear (AIS) equivalent and they have a sig-nificantly lower sensitivity to am-bient factors.

As in AC power systems, DC GIS technology spans a number of switchgear components, eg, bus ducts, disconnect switches, earthing switches, and current and voltage measurement sensors → 1. DC GIS has two principal advantages: Installations can be made far more compact than the AIS equivalent and they have a significantly lower sensitivity to ambient factors.

The most obvious cost-saving potential can be found on offshore converter platforms where the air clearance required for AIS would lead to a large and heavy offshore structure. By using DC GIS, where the live parts are encapsulated in a pressurized and grounded enclosure, the need for air clearance around the components is completely eliminated and the volumetric space of the switchgear component can be drastically reduced, typically by 70 to 90 percent. Furthermore, the space savings obtained can accommodate new functionality. An example of this functionality is a multiterminal DC system (MTDC) – ie, a set of onshore or offshore marshalling points for multiple cable connections. Using these, an offshore wind park with a converter platform can be connected to different grids in different countries, combining the utility of wind park grid

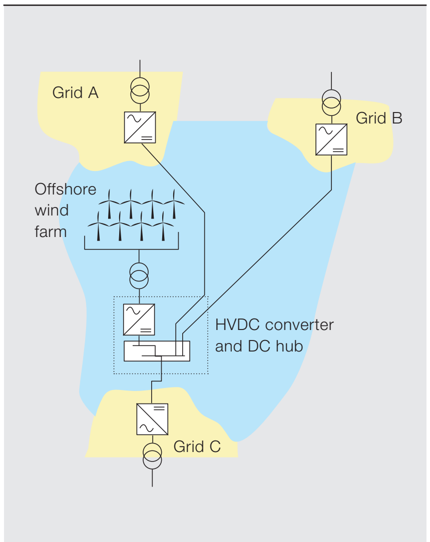
It is anticipated that DC GIS com-ponents with rat-ings up to 500 kV DC will be devel-oped and offered to the market in the near future.

connection with the facility of cross-border trading → 2. This increases the utilization of the cables and the security of supply, and can provide redundancy of the wind park transfer capacity in case of capacity reduction at one of the receiving ends.

HVDC installations on shore may also be drastically reduced in footprint and building height by applying DC GIS to selected components of the converter station.

Due to the combination of solid and gaseous insulation in GIS and the composite dielectric stress of both direct and impulse voltages, special care needs to be taken in the design of the insulating components. The support insulators inside the enclo-

2 DC GIS can provide compact grid interconnections in multiterminal HVDC systems.



The most obvious cost-saving potential can be found on offshore converter platforms where the air clearance required for AIS would lead to a large and heavy offshore structure.

sure, also known as GIS spacers, must be able to withstand not only the direct rated voltage but also transient switching and lightning overvoltages of different polarities. All these factors need to be considered in the design of the insulators.

A direct application of existing AC GIS components is typically not possible but these have been shown to be an excellent starting point in developing DC GIS components [1].

Based on the fact that well-established AC GIS technology with voltage ratings up to 1.1 GV is available, it can be anticipated that DC GIS components with ratings up to 500 kV DC will be developed and offered to the market in the near future.

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