HVDC

ABB – from pioneer to world leader

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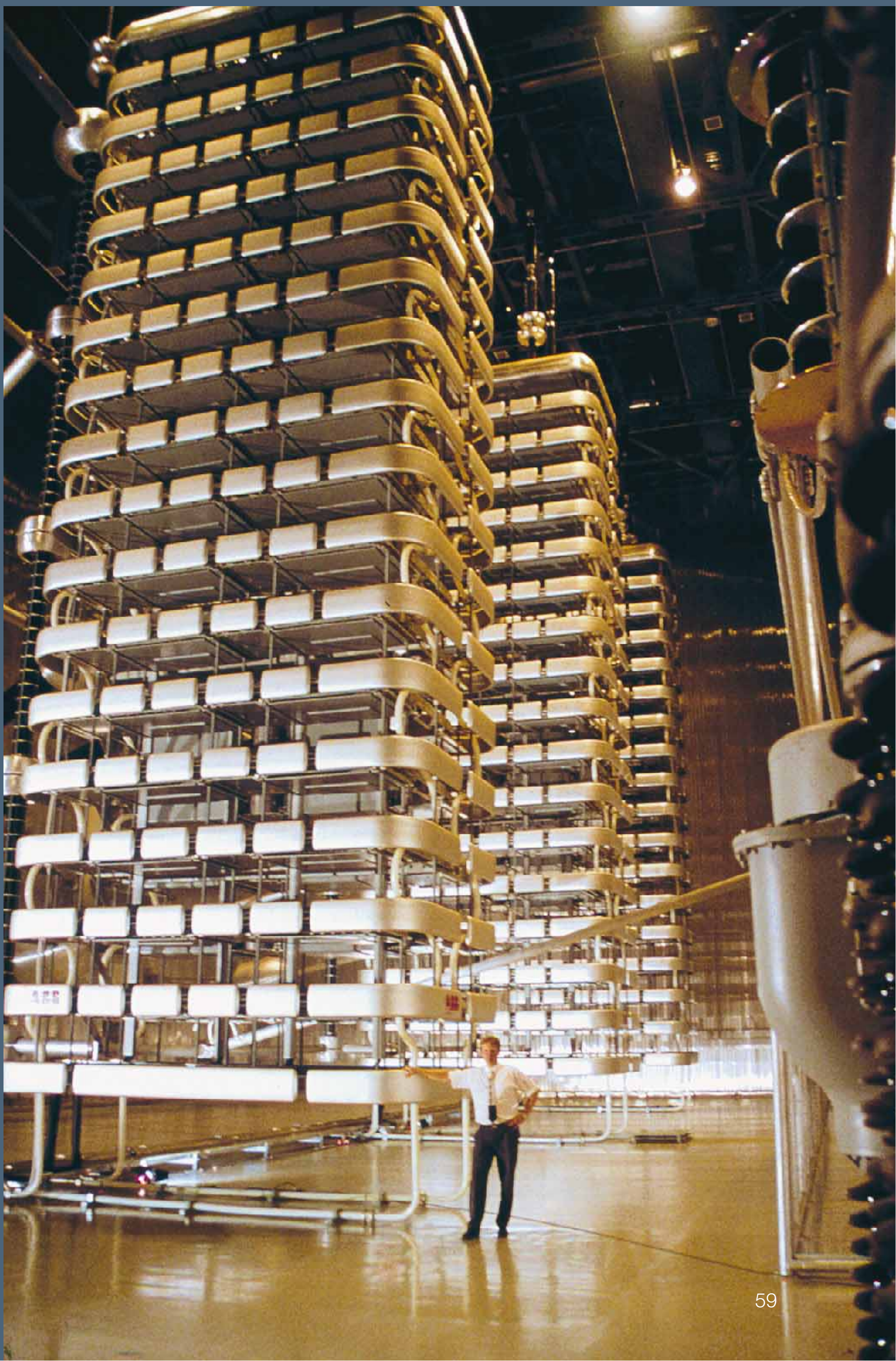


In 1954, at a time when much of Europe was busy expanding its electricity supply infrastructure to keep pace with surging demand, an event was quietly taking place on the shores of the Baltic Sea that would have a lasting effect on long-distance power transmission. Four years earlier, the Swedish State Power Board had placed an order for the world's first commercial high-voltage direct current (HVDC) transmission link, to be built between the Swedish mainland and the island of Gotland. Now, in 1954, it was being commissioned.

Today ABB proudly looks back at its many contributions to HVDC technology. Since the laying of that early 90 kilometers long, 100 kV, 20 MW submarine cable, our company has gone on to become the undisputed world leader in HVDC transmission. Of the 110,000 MW of HVDC transmission capacity currently installed all over the world, more than half was supplied by ABB.

PERPETUAL PIONEERING

With the arrival of the electric light bulb in the homes and factories of late 19th century Europe and the USA, demand for electricity grew rapidly and engineers and entrepreneurs alike were soon busily searching for efficient ways to generate and transmit it. The pioneers of this new technology had already made some progress – just being able to transmit power a few kilometers was regarded as something fantastic – when an answer to growing demand was found: hydroelectric power. Almost immediately, interest turned to finding ways of transmitting this cheap electricity to consumers over longer distances.

Analog simulator used in the design of the early HVDC transmission systems

First direct, then alternating current

The first power stations in Europe and the USA supplied low-voltage, direct current (DC) electricity, but the transmission systems they used were inefficient. This was because much of the generated power was lost in the cables. Alternating current (AC) offered much better efficiency, since it could easily be transformed to higher voltages, with far less loss of power. The stage was thus set for long-distance high-voltage AC (HVAC) transmission.

In 1893, HVAC got another boost with the introduction of three-phase transmission. Now it was possible to ensure a smooth, non-pulsating flow of power.

Although direct current had been beaten at the starting gate in the race to develop an efficient transmission system, engineers had never completely given up the idea of using DC. Attempts were still being made to build a high-voltage transmission system with series-connected DC generators and, at the receiving end, series-connected DC motors – all on the same shaft. This worked, but it was not commercially successful.

AC dominates

As the AC systems grew and power increasingly was being generated far from where most of its consumers lived and worked, long overhead lines were built, over which AC at ever-higher voltages flowed. To bridge expanses of water, submarine cable was developed.

Neither of these transmission media was without its problems, however. Specifically, they were caused by the reactive power that oscillates between the capacitances and inductances in the systems. As a result, power system planners began once again to look at the possibility of transmitting direct current.

Even when HVDC transmission finally proved technically feasible, it was doubted for a long time whether it could compete with HVAC in the marketplace.

Back to DC

What had held up high-voltage direct current transmission in the past was, first and foremost, the lack of reliable and economic valves that could convert HVAC into HVDC, and vice versa.

The mercury-arc valve offered, for a long time, the most promising line of development. Ever since the end of the 1920s, when the Swedish ASEA – a founding company of ABB – began making static converters and mercury-arc valves for voltages up to about 1000 V, the possibility of developing valves for even higher voltages had been continually investigated.

This necessitated the study of new fields in which only a limited amount of existent technical experience could be applied. In fact, for some years it was debated whether it would be possible at all to find solutions to all the various problems. When HVDC transmission finally proved to be technically feasible there still remained uncertainty as to whether it could successfully compete with HVAC in the marketplace.

Whereas rotating electrical machines and transformers can be designed very precisely with the aid of mathematically formulated physical laws, mercury-arc valve design depends to a large degree on knowledge acquired empirically. As a result, attempts to increase the voltage in the mercury-vapor-filled tube by enlarging the gap between the anode and cathode invariably failed.

The problem was solved in 1929 by a proposal to insert grading electrodes between the anode and cathode. Subsequently patented, this innovative solution can in some ways be considered as the cornerstone of all later development work on the high-voltage mercury-arc valve. It was during this time that Dr. Uno Lamm, who led the work, earned his reputation as the "father" of HVDC'.

The Gotland link

The time was now ripe for service trials at higher powers. Together with the Swedish State Power Board, the company set up, in 1945, a test station at Trollhättan, where there was a major power plant that could provide energy. A 50 km power line was also made available.

Trials carried out over the following years led to the Swedish State Power Board placing, in 1950, an order for equipment for the world's first HVDC transmission link. This was to be built between the island of Gotland in the Baltic Sea and the Swedish mainland.

Following on this order, the company intensified its development of the mercury-arc valve and high-voltage DC cable, while also initiating design work on other components for the converter stations. Among the equipment that benefited from the increased efforts were transformers, reactors, switchgear and the protection and control equipment.

Only some of the existing AC system technology could be applied to the new DC system. Completely new technology was therefore necessary. Specialists in Ludvika, led by Dr. Erich Uhlmann and Dr. Harry Forsell, set about solving the many very complex problems involved. Subsequently, a concept was developed for the Gotland system. This proved to be so successful that it has remained basically unchanged right down to the present time!

Since Gotland is an island and the power link was across water, it was also necessary to manufacture a submarine cable that could carry DC. It was seen that the "classic" cable with mass impregnated paper insulation that had been in use since 1895 for operation at 10 kV AC had potential for further development. Soon, this cable was being developed for 100 kV DC!

Finally, in 1954, after four years of innovative endeavor, the Gotland HVDC transmission link, with a rating of 20 MW, 200 A and 100 kV, went into operation. A new era of power transmission had begun.

The original Gotland link was to see 28 years of successful service before being finally decommissioned in 1986. Two new links for higher powers have meanwhile been built between the island and the Swedish mainland, one in 1983 and the other in 1987.

Early HVDC projects

The early 1950s also saw the British and French power administrations planning a power transmission link across the English Channel. High-voltage DC transmission was chosen, and the company won its second HVDC order – this time a link for 160 MW.

The success of these early projects generated considerable worldwide interest. During the 1960s several HVDC links were built: Konti-Skan between Sweden and Denmark, Sakuma in Japan (with 50/60 Hz frequency converters), the New Zealand link between the South and the North Islands, the Italy – Sardinia link and the Vancouver Island link in Canada.

> Continual development of the mercury-arc valve secured a level of reliability that has resulted in some HVDC projects with these valves still being in operation more than 40 years.

The largest mercury-arc valve HVDC transmission link to be built by the company was the Pacific Intertie [1] in the USA. Originally commissioned for 1,440 MW and later uprated to 1,600 MW at ± 400 kV, its northern terminal is sited in The Dalles, Oregon, and its southern terminal at Sylmar, in the northern tip of the Los Angeles basin. This project was undertaken together with General Electric, and started operating in 1970.

In all, the company installed eight mercury-arc valve based HVDC systems for a total power rating of 3,400 MW. Although many of these projects have since been replaced or upgraded with thyristor valves, some are still in operation today, after more than 40 years of service!

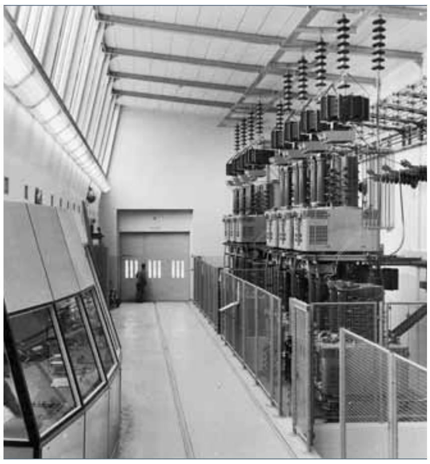
All through the first half of the 1960s, as a result of the huge interest being shown in semiconductor appli-cations, work had continued on development of high-voltage thyristor valves as an alternative to the mercury-arc type. In the spring of 1967, one of the mercury-arc valves used in the Gotland HVDC link was replaced with a thyristor valve. It was the first time anywhere that this kind of valve had been taken into commercial operation for HVDC transmission. After a trial of just one year, the Swedish State Power Board ordered a complete thyristor valve group for each converter station, at the same time increasing the transmission capacity by 50 percent.

Around the same time, 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 today.

The new valve groups were connected in series with the two existing mercury-arc valve groups, thereby increasing the transmission voltage from 100 to 150 kV. This higher-rated sys-

Early mercury-arc valve for HVDC transmission

Mercury-arc valves in the first Gotland link, 1954



PERPETUAL PIONEERING

Foz do Iguaçu converter station with the Itaipu 12,600 MW power station in the background

Baltic Cable HVDC converter station

tem was taken into service in the spring of 1970 – another world's "first" for the Gotland transmission link.

With the advent of thyristor valves it became possible to simplify the converter stations, and semiconductors have been used in all subsequent HVDC links. Other companies were now entering 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 1,920 MW Cahora Bassa HVDC link between Mozambique and South Africa. The same group then went on to build the 2,000 MW Nelson River 2 link in Canada. This was the first project to employ water-cooled HVDC valves.

The late 1970s also saw the completion of new projects. These were the Skagerrak link between Norway and Denmark, Inga-Shaba in the Congo, and the CU Project in the USA.

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. The Sylmar terminal is since 2004 equipped with thyristor converters for the full power capacity.

Itaipu – the new benchmark

The contract for the largest of all HVDC transmission schemes in the 20th century, the 6,300 MW Itaipu HVDC link in Brazil, was awarded to the ASEA-PROMON consortium in 1979. This project was completed and put into operation in several stages between 1984 and 1987. It plays a key role in the Brazilian power scheme, supplying a large portion of the electricity for the city of São Paulo.

The scale and technical complexity of the Itaipu project presented a considerable challenge, and it can be considered as the start of the modern HVDC era. The experience gained in the course of its completion has been in no small way responsible for the many HVDC orders awarded to ABB in the years since.

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The most challenging HVDC project in the late 1980s and in the early 1990s was undoubtedly the 2,000 MW Québec – New England link. This was the first large multi-terminal HVDC transmission system to be built anywhere in the world.

HVDC cables have kept pace

As the converter station ratings increased, so too did the powers and voltage levels for which the HVDC cables had to be built.

The most powerful HVDC submarine cables to date are rated 700 to 800 MW at 450 to 500 kV. The longest of these are the the 580 km NorNed link between Norway and The Netherlands taken in service in 2008.

HVDC today

The majority of HVDC converter stations built today are still based on the principles that made the original Gotland link such a success back in 1954. Station design underwent its first big change with the introduction of thyristor valves in the early 1970s. The first of these were air-cooled and designed for indoor use, but soon outdoor oil-cooled, oil-insulated valves were also being used. Today, all HVDC valves are water-cooled [2].

Good examples of modern bulk power HVDC transmission are the links ABB is installing for the Three Gorges hydroelectric power plant project in China.

In 1995 ABB presented a new generation of HVDC converter stations: HVDC 2000 [3]. HVDC 2000 was developed to meet stricter electrical disturbance requirements, to provide better dynamic stability where there was insufficient short-circuit capacity, to overcome space limitations, and to shorten delivery times.

A key feature of HVDC 2000 was the introduction of capacitor commutated converters (CCC). This was, in fact, the first fundamental change to have been made to the basic HVDC system technology since 1954!

HVDC 2000 also includes other ABB innovations, such as continuously tuned AC filters (ConTune), active DC filters, outdoor air-insulated HVDC valves, and the fully digital MACH2™ control system.

The first project to employ HVDC 2000 with CCC and outdoor valves was the Garabi 2,200 MW HVDC back-to-back station in the Brazil – Argentina HVDC Interconnection. The Apollo converter station (South Africa) in the Cahora Bassa transmission was equipped with new outdoor air-insulated HVDC valves in 2008.

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UHVDC

Until now, the majority of the largest HVDC transmissions rated 2,000 MW or more have been designed for voltages in the ± 500 to 600 kV range. But these levels were not sufficient for the transmissions of around 2,000 km from the giant hydro power stations now being in built China and India. Between 5,000 and 8,000 MW has to be sent over a single bipole in these transmissions. Ultra High Voltage DC (UHVDC) of ± 800 kV proved to be the optimal choice considering investments, losses and technical limitations. This called for major developments for the converter station equipment. ABB has developed equipment for the new DC voltage level and has performed long term tests on them. ABB is currently delivering ultrahigh-voltage technology for the world's longest power transmission link in China: Xiangjiaba – Shanghai ± 800 kV UHVDC transmission project, rated 6,400 MW. This 2,071 km long transmission will be commissioned in 2010 to 2011.

HVDC Light®

HVDC technology has become a mature technology over the past 50 years and reliably transmits power over long distances with very low losses. This begs the question: where is development work likely to go in the future?

It was conceived that HVDC development could, once again, take its cue from industrial drives. Here, thyristors were replaced a long time ago by voltage source converters (VSC), with semiconductors that can be switched off as well as on. These have brought many advantages to the control of industrial drive systems and it was realized that they could also apply to transmission systems. Adapting the technology of voltage source converters to HVDC, however, is no easy matter. The entire technology has to change, not just the valves.

As development of its VSC converter got under way, ABB realized that the insulated gate bipolar transistor, or IGBT, held more promise than all the other available semiconductor components. Above all else, the IGBT needs only very little power for its control, making series connection possible. However, for HVDC a large number of IGBTs have to be connected in series, something industrial drives do not need.

In 1994, ABB concentrated its development work on VSC converters in a project that aimed at putting two converters based on IGBTs into operation for small-scale HVDC. An existing 10-km-long AC line in central Sweden was made available for the project.

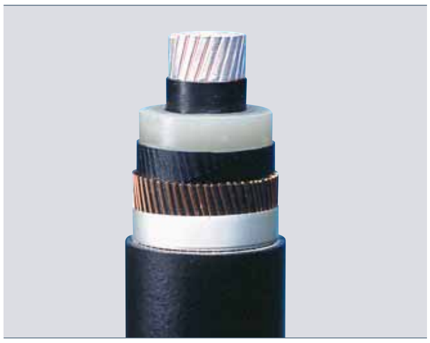
At the end of 1996, after comprehensive synthetic tests, the equipment was installed in the field for testing under service conditions. In 1997 the world's first VSC HVDC transmission system, HVDC Light® [4], began transmitting power between Hellsjön and Grängesberg in Sweden.

In the meantime, eleven such systems have been ordered, and eight of them are now in commercial operation around the world.

Laying the cable for the Gotland HVDC link in 1954

Submarine cable for the 600 MW Baltic Cable HVDC link between Germany and Sweden

HVDC Light land cable



STRI laboratory in Ludvika, Sweden with 800 kV UHVDC test installation

One advantage of HVDC Light is that it allows an improvement in the stability and reactive power control at each end of the network. Also, it can operate at very low short-circuit power levels and even has black start capability.

In 1997 the world's first VSC HVDC transmission system, HVDC Light, began transmitting power between Hellsjön and Grängesberg in Sweden.

HVDC Light was from the beginning a technology for underground or submarine cable transmissions and a special HVDC Light cable was developed. The HVDC Light cable is made of polymeric material and is therefore very strong and robust. This makes it possible to use HVDC cables where adverse laying conditions might otherwise cause damage. Extruded cable has also made very long HVDC cable transmission on land now economically viable. An example is the 180-km-long HVDC Light interconnection Murraylink in Australia.

The NordE.ON 1 connection from an offshore wind power park to Gemany and the Troll and Valhall connections to feed offshore oil and gas production platforms from land (Norway) are interesting applications, where the small weight and space requirement of the HVDC Light converter is essential as well as the HVDC Light cable [4].

The Caprivi Link Interconnector in Namibia is the first HVDC Light transmission that will use a DC overhead line. This link is presently being delivered and it will start to transmit power in 2009. This adaptation of the HVDC Light technology will greatly broaden the range of applications.

And the next 50 years?

HVDC transmission has come a long way since that first Gotland link. But what does the future hold for it?

UHVDC is already here and transmissions of ± 800 kV and power levels of more than 6,000 MW are being built. This voltage will mainly be used for large bulk power transmissions from remote hydropower resources. Higher voltages are possible but this requires extensive development efforts.

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The authors' prediction is that HVDC Light will take over the market from thyristor-based technology except for the largest power levels in the future. The drawbacks of higher converter station losses for the VSC technology over conventional HVDC that has existed in the past is likely to disappear within a few years. The adaptation of the HVDC Light technology to DC overhead lines makes it possible to go beyond the limitations of DC cables already today.

The most interesting prospects for HVDC Light, however, lie in its potential for building multi-terminal systems and even DC networks. In the long term this might offer a solution for "backing up" the AC grids for long-distance transmission. This is particularly of interest in grids that were orginally designed for reserve purposes and hence use a voltage level not appropriate for long-distance AC transmission.

Further information on HVDC can be found at www.abb.com/hvdc

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References

[1] **Engström, L.** More power with HVDC to Los Angeles. *ABB Review* 1/88, 3–10.
[2] **Sheng, B., Bjarma, H. O.** Proof of performance – a synthetic test circuit for verifying HVDC thyristor valve design. *ABB Review* 3/2003, 25–29.
[3] **Aernlöv, B.** HVDC 2000 – a new generation of high-voltage DC converter stations. *ABB Review* 3/1996, 10–17.
[4] **Asplund, G. et al.** HVDC Light – DC transmission based on voltage sourced converters. *ABB Review* 1/1998, 4–9.
[5] **Nestli, T. et al.** Powering Troll with new technology. *ABB Review* 2/2003, 15–19.