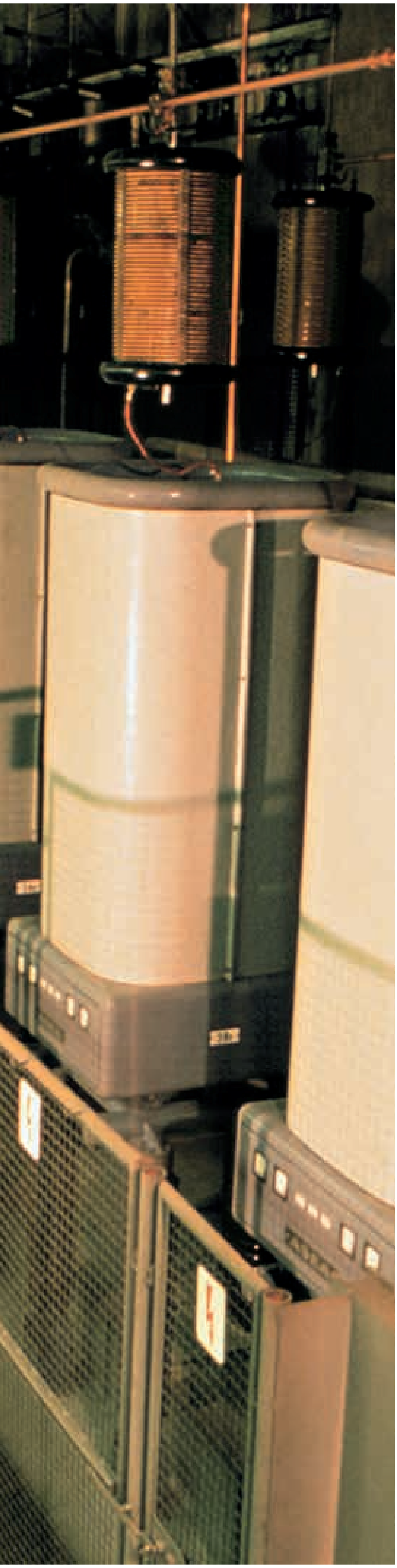
60 years of HVDC

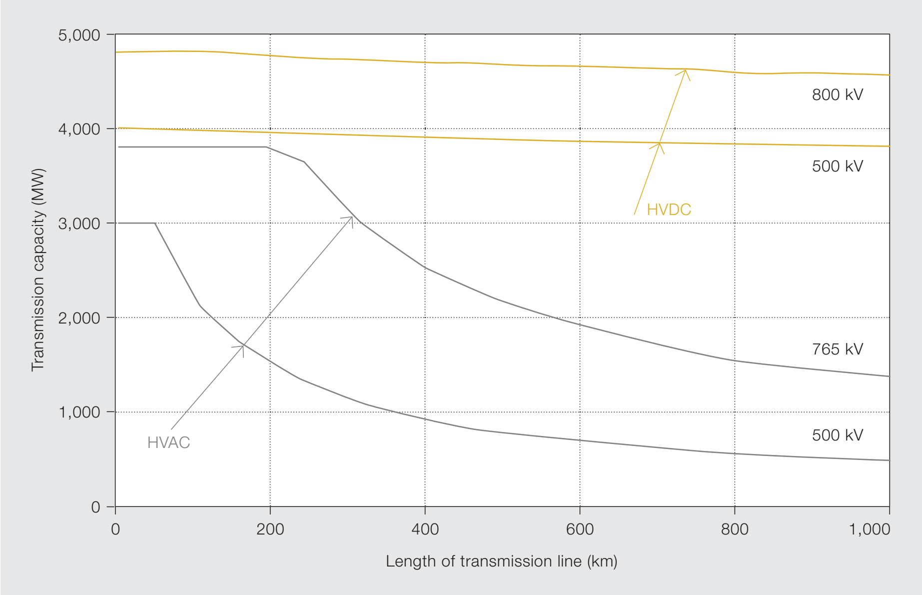
ABB's road from pioneer to market leader

ANDREAS MOGLESTUE – Looking back on the clash between Edison's DC and Tesla's AC in the "War of the Currents" of the 1880s, it is often summarily assumed that the question was settled once and for all. But during the last 60 years, DC – at higher voltages than Edison could have imagined, has been making a steady comeback. HVDC is now an indispensable part of transmission grids across the world, and is set to expand into further markets still. The history of ABB is intricately intertwined with that of HVDC: ABB's predecessor companies pioneered the technology and ABB is not only firmly established as market leader today, but is the only company able to supply the complete scope of HVDC components, including the overall engineering as well as transformers, converter stations, semiconductors, cables and control systems.



Title picture
The world's first HVDC thyristor valves (foreground) connected in series with the original converter (background) at Gotland (circa 1970)

1 Reactive power limits the distance over which AC transmission is viable.



The transmission of electricity over large distances requires high voltage levels. Because ohmic losses are proportional to the square of the current, every doubling of the voltage reduces losses to one quarter. The simplest way of achieving high voltage levels is to use transformers. But unfortunately for the DC faction during the War of the Currents, the principle of transformation only applies to AC. DC's principal proponent, Thomas Edison, was however not one to give up easily. Rather than admitting defeat over this simple fact of physics, he resorted to a double-pronged counter-attack. On the one hand he drew attention to the safety hazards of higher voltages, sometimes resorting to horrific methods to instill public distrust of them (he once had an elephant electrocuted and also played a part in the creation of the first electric chair). As an alternative to high-voltage transmission, Edison promoted local generation. This meant providing a power plant in every neighborhood (the limit for the commercial transmission of 110 V DC being about 1.6 km). Although the urban pollution from such plants would have been problematic (especially considering the generation technology of the day), and the very suggestion may sound risible through the perspective of history, Edison's idea is enjoying some revindication at present through the concept of microgeneration – in which customers can feed self-generated electricity (eg, solar) into the grid.

The second prong of Edison's counterattack was to try his own hand at transmitting electricity at higher voltages (seemingly in discord with his anti-high-voltage activism). In 1889, Edison built a 22 km line from Williamette Falls to Portland, Oregon (United States) transmitting about 130 kW at 4 kV. The voltage level was obtained through the series connection of generators (a principle that was first demonstrated at an exhibition in Munich, Germany, in 1882). Symptomatically with the demise of DC, the Oregon line was to be short-lived: It was heavily damaged by a flood in 1890 and then rebuilt as an AC installation by Edison's competitor, Westinghouse.

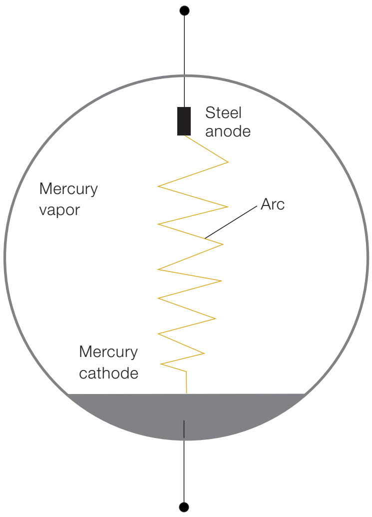
Already during Edison's lifetime, DC was growing in many sectors.

But the history of DC transmission did not end with that flood. As late as 2006 there were still 60 customers connected to the Edison DC supply in New York City (the supply was finally switched off the following year). But much more significantly, already during the inventor's lifetime, DC was growing in sectors such as rail transportation, aluminum smelting and telecommunications, in all of which it is still of great significance today. New applications added since include data processing and photovoltaics. However, in terms of transmission and distribution, AC's superiority appeared unassailable. But was it really?

Drawbacks of AC

Despite the rapid adoption of three-phase AC for transmission and distribution, longer AC lines face drawbacks. The most important of these is the phenomenon of reactive power. Reactive power is the flow of energy that continuously charges and discharges the line's electric and magnetic fields to accommodate the periodic oscillation of the line's voltage and current. Although not directly wasteful (the energy is recovered as the fields discharge), the additional current and voltage on the line subtract from its useful economic capability. As capacitance and inductance increase with the length of the line, reactive power also grows until a point is reached that commercial transmission ceases to be viable. It is ironic that the laws of physics that enable transformation and make high-voltage AC transmission possible in the first place are the same laws that ultimately limit the distance over which it is useful → 1.

2 Mercury-arc valve



3 Uno Lamm, the "father of HVDC," in the control room of the Gotland HVDC

There are solutions to the reactive power challenge – for example FACTS devices that compensate reactive power. However, DC transmission eliminates the problem entirely as the line's electric and magnetic fields are constant and thus only need to charged when the line is powered up.

Mercury-arc valves

Early attempts at DC transmission at higher voltages relied on the series connection of generators or motor-generators.[1] The principle was thus limited by mechanical constraints and was unable to economically compete with AC.

Interest in DC conversion resurged when a new technology came onto the scene: the mercury-arc valve.[2] This valve is a sealed bulb filled with mercury vapor using steel anodes and a mercury cathode → 2. Once an arc is initiated between anode and cathode, the current flowing in the arc generates heat and ionizes the mercury vapor. At the interface of the arc and the mercury, the bombardment by ions causes electrons to be released. The steel can absorb electrons but does not release significant quantities at the operating temperature. Current can thus flow from the steel to the mercury but not in the reverse direction. The mercury valve thus displays diode functionality, making it suitable for AC to DC conversion.

But mercury valves can also perform the reverse (DC to AC) conversion: An artificial triggering of the arc (using an inductor to apply a voltage peak to an auxiliary electrode) permits conduction to commence at an arbitrary point in the cycle.

By being able to perform both conversions, mercury valves permitted the use of transformers, thus combining the transformation advantages of AC with the transmission advantages of DC.

The mercury arc valve was first demonstrated in 1902 by the American inventor Peter Cooper Hewitt. ABB's predecessor company, BBC (Brown, Boveri & Cie), was a leader in their development, with commercialization beginning in 1913. Early installations, however, did not target DC transmission but were used to rectify lower voltages (up to about 2,500 V) for industrial and transportation purposes.[3]

One of the problems encountered as voltages were increased was that of arc-back. An arc-back occurs when a reverse voltage across an unignited valve sparks

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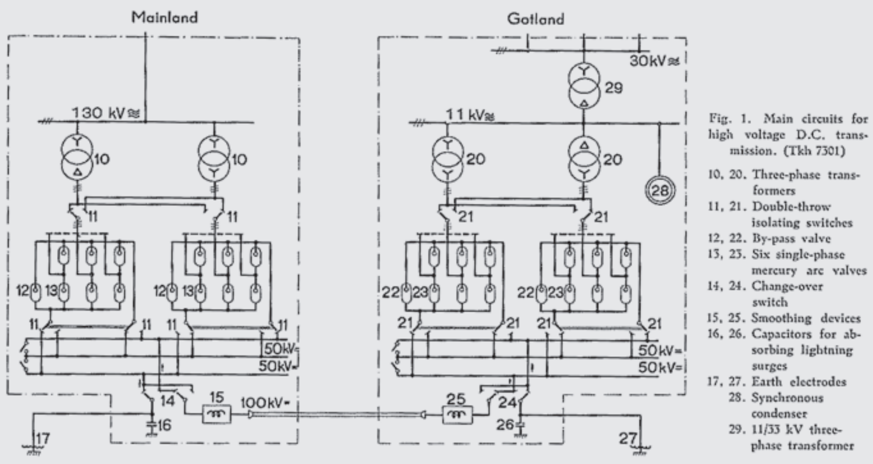
Footnotes

1 A motor generator is a motor and generator pair sharing the same shaft. An array of motor-generators can be used to increase DC voltages by connecting the motors in parallel but the generators in series.

2 Mercury arc valves and ABB's part in their development are discussed in greater length in "From mercury arc to hybrid breaker" in *ABB Review* 2/2013, pages 70–78.

3 Nevertheless, BBC did demonstrate a temporary DC transmission in 1939. It transmitted 500 kW at 50 kV over 25 km between Wettingen and Zurich in Switzerland.

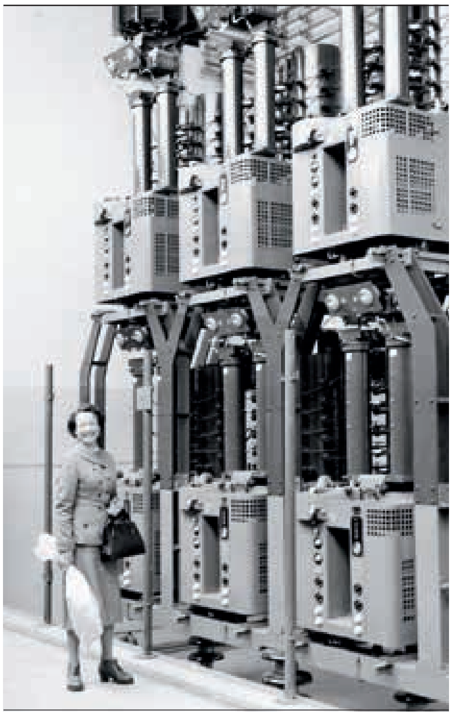
4 Schematic of the Gotland link, showing the series connection of converters in both stations



The synchronous condenser (28) was to control reactive power and assure local commutation on the Gotland side (the link replaced a local power plant; there was thus no local commutation).

ASEA Journal, 1954, p. 142

5 The three valves of one converter of the Gotland link (with Lamm's wife, Pamela)



The Gotland link provided many new challenges for ASEA, not least of which was the sea crossing.

an involuntary arc in the reverse direction. This not only causes a malfunction of the circuit but can cause permanent damage to the valve. It was another of ABB's predecessor companies, ASEA (Allmänna Svenska Elektriska Aktiebolaget) that was to provide the next breakthrough. In 1929, Uno Lamm → 3 was awarded a patent for controlling arc-back by using grading electrodes. Grading electrodes are intermediate electrodes connected to a voltage divider to prevent an arc from being able to form from anode to cathode in a single strike. For this work and its consequences, Lamm is often called "the father of HVDC."

Despite this patent, the road from the basic idea to a reliable implementation was long. Due to the often unpredictable behavior of arcs, valve development was very much a process of empirical research. In order not to destabilize the electrical grid in the town of Ludvika (where the development lab was located) high-power trials had, at times, to be restricted to nightly hours.

The Swedish State Power Board (SSPB, now Vattenfall) followed ASEA's progress with interest. By the early 1940s, the technology was sufficiently mature for a trial converter station to be built. Trollhättan was chosen as the location for this (due to the adjoining power plant). Construction commenced in 1943, with operation beginning in 1945. A 50 km, 6.5 MW, 90 kV line was built to Mellerud, where another converter station was added. This transmission line was built purely for test purposes, a role it continued to fulfill until its decommissioning the late 1960s.

Gotland

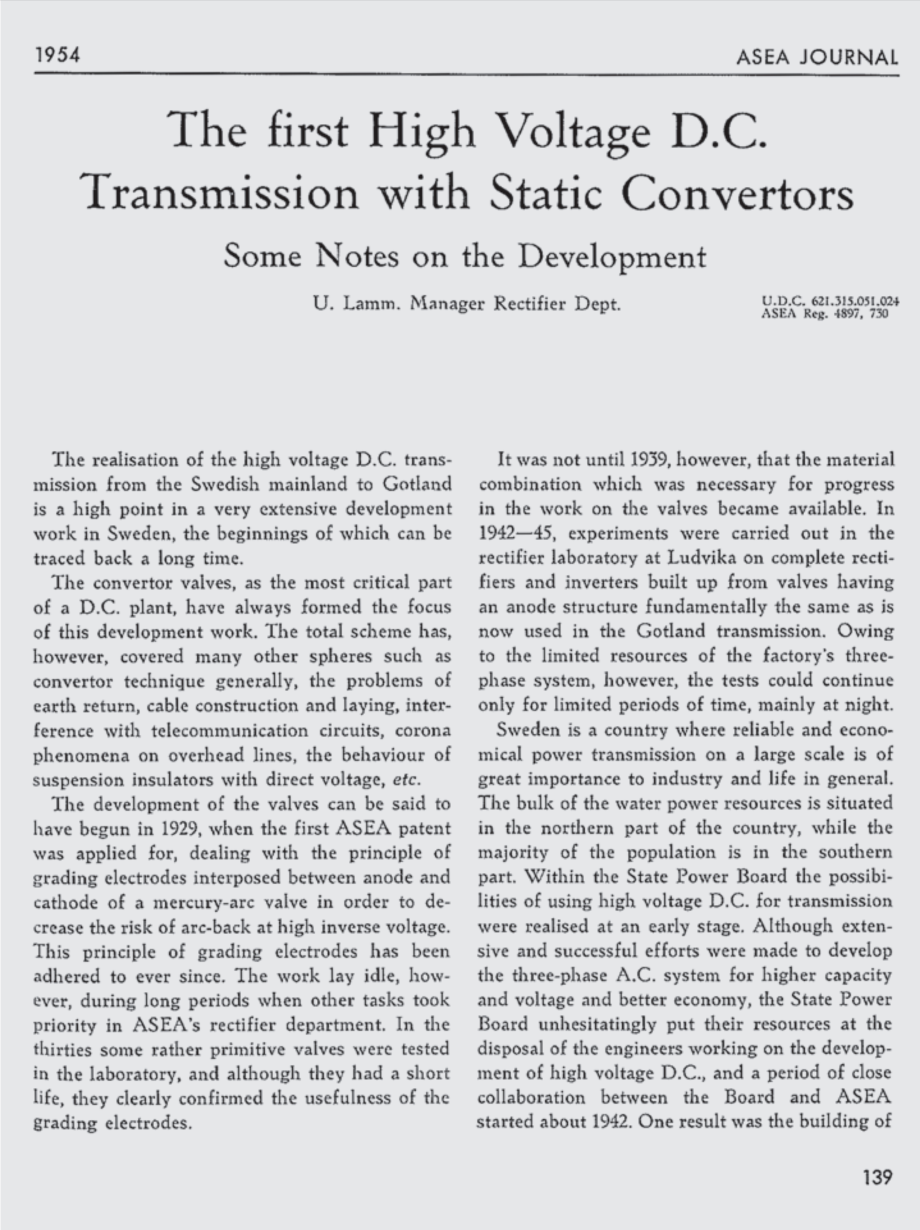
In 1950 Swedish parliament approved an HVDC link between the island of Gotland and the Swedish mainland → 4 – 5. This link provided many new challenges for ASEA, not least of which was the sea crossing. For this purpose, an underwater cable was developed.

On March 7, 1954, the 200 A link was powered up, initially at 50 kV. This was doubled to 100 kV on July 26, when the second pair of converters were added in series. The era of commercial HVDC had begun.

The *ASEA Journal* marked the event with an article penned by Lamm himself → 6. He opens with the words:

"The realization of the high voltage D.C. transmission from the Swedish mainland to Gotland is a high point in a very extensive development work in Sweden, the beginnings of which can be traced back a long time".

6 First page of Lamm's article from the *ASEA Journal* of 1954, presenting the Gotland link



1954 ASEA JOURNAL

The first High Voltage D.C. Transmission with Static Convertors

Some Notes on the Development

U. Lamm. Manager Rectifier Dept.

U.D.C. 621.315.051.024
ASEA Reg. 4897, 730

The realisation of the high voltage D.C. transmission from the Swedish mainland to Gotland is a high point in a very extensive development work in Sweden, the beginnings of which can be traced back a long time.

The convertor valves, as the most critical part of a D.C. plant, have always formed the focus of this development work. The total scheme has, however, covered many other spheres such as convertor technique generally, the problems of earth return, cable construction and laying, interference with telecommunication circuits, corona phenomena on overhead lines, the behaviour of suspension insulators with direct voltage, *etc.*

The development of the valves can be said to have begun in 1929, when the first ASEA patent was applied for, dealing with the principle of grading electrodes interposed between anode and cathode of a mercury-arc valve in order to decrease the risk of arc-back at high inverse voltage. This principle of grading electrodes has been adhered to ever since. The work lay idle, however, during long periods when other tasks took priority in ASEA's rectifier department. In the thirties some rather primitive valves were tested in the laboratory, and although they had a short life, they clearly confirmed the usefulness of the grading electrodes.

It was not until 1939, however, that the material combination which was necessary for progress in the work on the valves became available. In 1942—45, experiments were carried out in the rectifier laboratory at Ludvika on complete rectifiers and inverters built up from valves having an anode structure fundamentally the same as is now used in the Gotland transmission. Owing to the limited resources of the factory's three-phase system, however, the tests could continue only for limited periods of time, mainly at night.

Sweden is a country where reliable and economical power transmission on a large scale is of great importance to industry and life in general. The bulk of the water power resources is situated in the northern part of the country, while the majority of the population is in the southern part. Within the State Power Board the possibilities of using high voltage D.C. for transmission were realised at an early stage. Although extensive and successful efforts were made to develop the three-phase A.C. system for higher capacity and voltage and better economy, the State Power Board unhesitatingly put their resources at the disposal of the engineers working on the development of high voltage D.C., and a period of close collaboration between the Board and ASEA started about 1942. One result was the building of

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The latter paragraph would not look out of place in any publication on HVDC of the past 60 years: The basic principles established for Gotland still hold today, with ASEA (and later ABB) having built up expertise in all of the areas mentioned. In fact ABB is today the only company worldwide that is able to provide from a single hand all parts of an HVDC system, ranging from transformers, converter stations and their components, to the cables, control systems and more recently, breakers.

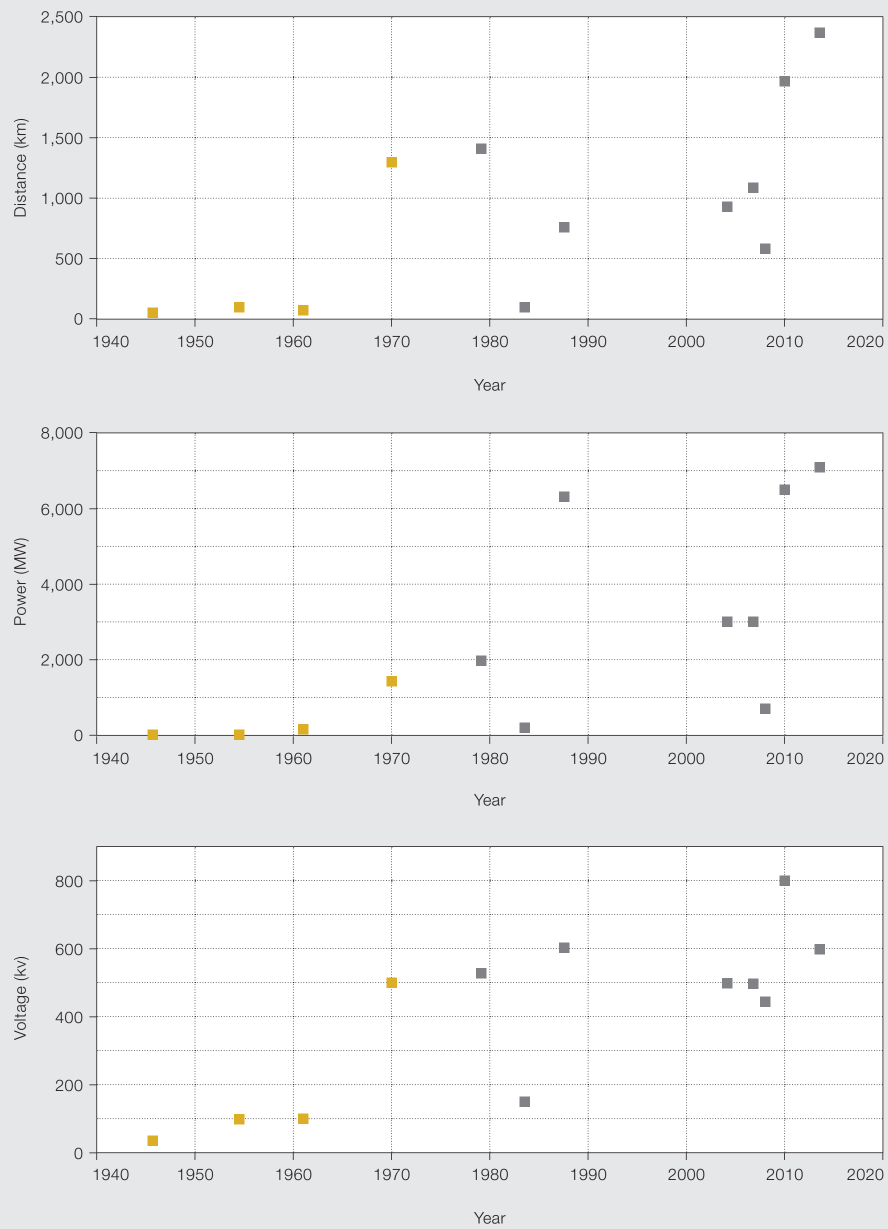
ASEA's second commercial HVDC project was a 160 MW link between Britain and France, inaugurated in 1961. Further projects, ranging from Scandinavia to Italy, Japan, Canada and New Zealand, followed in the 1960s, several of them again involving sea crossings using cables. The culmination of the development of mercury-arc based HVDC was the Pacific Intertie, a 1,300 km, 1,440 MW (raised to 1,600 MW in 1982), 500 kV link between Celio (Oregon) and Sylmar (southern

ASEA's labs commenced thyristor development in the mid-1960s.

As an alternative to high-voltage transmission, Edison promoted local generation.

7 A selection from numerous HVDC projects delivered by ABB. The company has supplied more than half the world's 170 projects.

Year	Project	Converters	Distance (km)	Power (MW)	Voltage (kV)
1946	Trollhättan - Mellerud (test line)	Mercury-arc valves	50	6,5	45
1954	Gotland 1		98	20	100
1961	English Channel		64	160	100
1970	Pacific Intertie		1300	1,440	500
1979	Cahora Bassa	Silicon	1420	1,920	533
1983	Gotland 2		99	130	150
1987	Itaipu		780	6,300	600
2004	Three Gorges – Guangdong		940	3,000	500
2007	Three Gorges to Shanghai		1060	3,000	500
2008	NorNed		580	700	450
2010	Xiangjiaba – Shanghai		1980	6,400	800
2013	Rio Madeira		2375	7,100	600



8 An early ASEA thyristor-based converter

HVDC Light uses voltage source converters (VSCs) with IGBTs, a technology derived from that used in industrial drives.

California), built jointly with General Electric (GE) and inaugurated in 1970.

Until ceasing development of mercury-arc valves in 1971, ASEA had used them in links with a total power of 3,400 MW → 7.

Thryristors

Commencing in the 1960s, a new type of valve came onto the scene, ultimately to displace mercury-arc technology → 8.

The principle of the thyristor was first proposed by William Shockley in 1950. A thyristor is a semiconductor device with three terminals (anode, cathode and gate). As in a semiconductor diode, current conducts in one direction only, with a reverse voltage depleting charge carriers from the junction area. The thyristor has additional layers between the p- and n-zones that normally also prevent conduction, but the application of a trigger current to the gate floods this area with charge carriers and permits conduction. Once conduction is initiated, the production of charge carriers becomes self-sustaining and the gate current can be removed. Conduction does not cease until the main current falls below a threshold value. The overall functionality is thus broadly comparable to that of a triggerable mercury-arc valve, but with the advantage of being much more compact, having lower losses and eliminating the risks that come with handling mercury as well as being well suited to the series connection of multiple devices to create valves for higher voltages.

ASEA commenced thyristor development in the mid 1960s. In 1967 a test converter station was fitted to the Gotland link. In 1970, thyristor converters were added in series to the existing mercury-arc stations → title picture, raising the operating voltage to 150 kV (while retaining the original cable, which had no trouble coping with the increased voltage.)[4]

HVDC projects delivered during the 1970s include the Skagerak link between Norway and Denmark, Inga-Shaba in the Congo, the CU project in North Dakota, United States, and Nelson River 2 in Canada.

During the mercury-arc era, ASEA had been practically alone in the market for HVDC, but the disruptive innovation caused by the greater simplicity of working with thyristors enabled many new competitors to enter the field. BBC, for example, teamed up with Siemens and AEG to supply the Cahora Bassa link between Mozambique and South Africa in the mid-1970s. ASEA responded to the new competition by investing in research to establish its leadership in HVDC thyristors.

A landmark project of the 1980s was the 6,300 MW Itaipu link in Brazil, awarded to a consortium of ASEA and PROMON, which was put into service in stages between

Footnote

4 The Gotland 1 link remained in use until 1986. Today the island is connected by two HVDC links, Gotland 2 and 3, commissioned in 1983 and 1987, respectively, with a total capacity of 260 MW.

As early as 1992, ABB proposed a grid of HVDC lines as an overlay over the existing power grid, relieving it of long-distance bulk flows.

9 The Jingzhou station of the Three Gorges Guangdong HVDC link

1984 and 1987. The 2,000 MW Québec – New England project delivered around the same time link was the world's first multiterminal HVDC link.

In 1988, ASEA and BBC merged to form ABB. In 1995, the company launched a new generation converter station. A key feature was the use of capacitor commutated converters (CCCs), permitting valves to be switched off rather than having to wait for a current zero crossing. This was the most fundamental change in switching since 1954, and permitted an improvement in controllability and reduction in reactive power. The first project to use this technology was the 2,200 MW Brazil – Argentina (Garabi) interconnection of 1999.

ABB continued to raise voltage and power levels. In 2004, the Three Gorges – Guangdong HVDC link (China) was opened, transmitting 3,000 MW over 940 km at ± 500 kV → 9. In 2007, a 1,060 km link of the same ratings connected Three Gorges to Shanghai. 2010 saw the Xiangjiaba – Shanghai ± 800 kV, 6,400 MW, 1,980 km UHVDC (ultrahigh-voltage DC) link go into service. In 2013, the Rio Madeira link in Brazil began transmitting 7,100 MW over 2,375 km.

But HVDC is not just about ever larger power ratings spanning ever growing distances. Continuing in the tradition of the Gotland link, HVDC is also highly suitable for underwater connections, where it already displays advantages over HVAC on distances measured in tens of km (due to the higher capacitance of sheathed cables versus lines) → 10. For example, in 2008, the NorNed link bridged the 580 km between Norway and the Netherlands.

Going light

On a smaller scale, HVDC can also be used to connect offshore windparks or supply power to oil and gas platforms → 11. For the lower power classes, ABB introduced HVDC Light® in the 1990s. Rather than using thyristor valves, HVDC Light uses voltage source converters (VSCs) with IGBTs, a technology derived from that used in industrial drives. The higher controllability, reactive power control capability and black start capability of HVDC Light means it can be connected to island networks with no local commutation, but can also be used to relieve pressure on or stabilize existing AC grids. The compact design of HVDC Light means converter stations can be fitted inside containers and delivered to site in one piece, simplifying testing and commissioning.

The HVDC grid

Many new challenges face tomorrow's power grids. Not the least among these is the radical transformation of the generation landscape. Traditional power plants were mostly built close to the centers of consumption, but the rapidly increasing market share of renewables means that more and more power is coming from remoter regions. This power must be transmitted over long distances, often through areas where the traditional grid is weak and not suited to handle the extra load. As

10 Cable of the Fenno Scan HVDC link being loaded onto a ship. This link was completed in 1989.

11 Lifting an HVDC Light offshore module into position on a North Sea oil platform.

early as 1992, ABB's Gunnar Asplund proposed a grid of HVDC lines as an overlay over the existing power grid, relieving it of long distance bulk flows.

But building a DC grid is not as simple as it may sound. The main technical obstacle was the lack of a suitable breaker. In AC networks, breakers are used to quickly and safely isolate any section of line, for example in the case of a disturbance, without impacting the rest of the grid. When an AC breaker opens, an arc continues to conduct current between the contacts until the next zero crossing of the current. With DC not having such useful zero crossings, a different approach is required, and this has long prevented the development of more complex HVDC network topologies. ABB finally solved this conundrum in 2012. The hybrid breaker uses a combination of semiconductors and mechanical switches to break the DC flow in a safe and timely manner.[5]

DC or AC?

So, who really did win the War of the Currents? DC is advancing into areas that would traditionally have been AC applications, but it can never fully replace AC. Maybe, more than 120 years on, we can call it a draw: The history books of the future will give credit to both Tesla and Edison.

Footnote

5 See also "Breakthrough!: ABB's hybrid HVDC breaker, an innovation breakthrough enabling reliable HVDC grids" in *ABB Review* 2/2013 pp. 6–13.

Andreas Moglestue
ABB Review
Zurich, Switzerland
andreas.moglestue@ch.abb.com

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