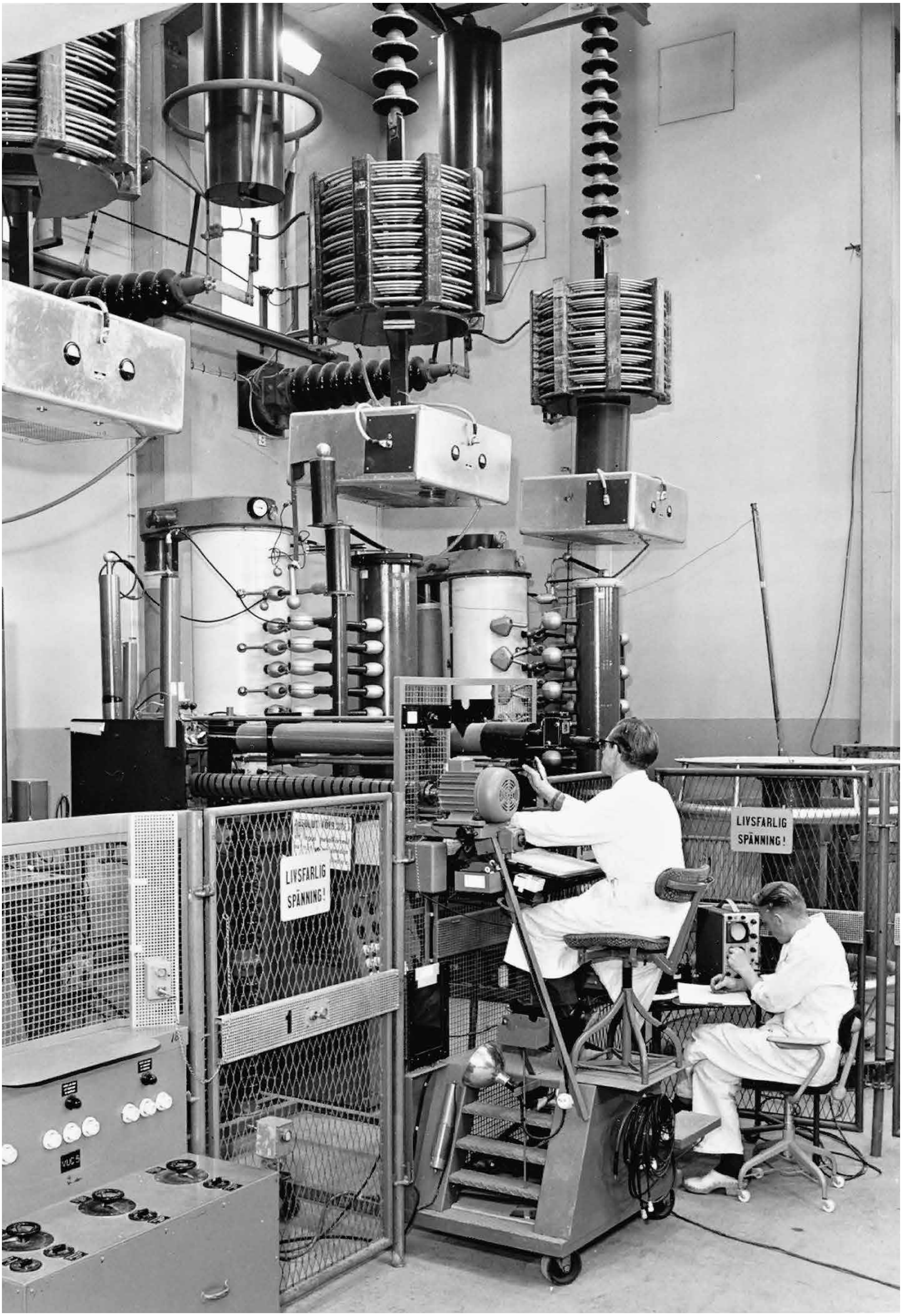
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High impact

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.

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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.

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.

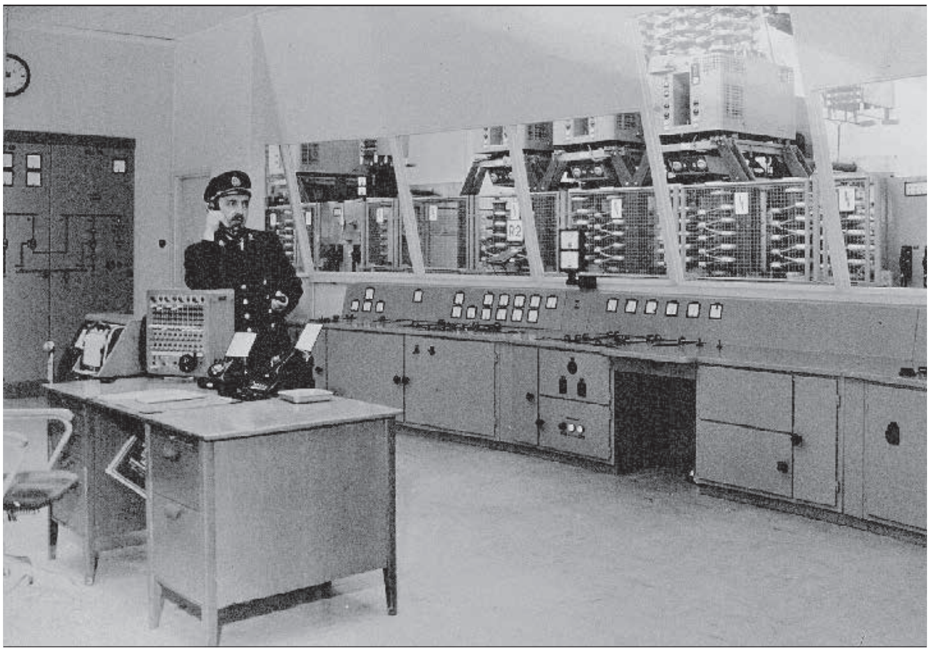
1 Dr. Uno Lamm, "the father of HVDC"

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. 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

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.

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

Bo Pääjärvi
Mie-Lotte Bohl
ABB Power Systems
Ludvika, Sweden
bo.paajarvi@se.abb.com
mie-lotte.bohl@se.abb.com