



HVDC veterans' presentations

We are delighted to be able to present two of the ABB HVDC veterans' speeches at the 2004-05-06 celebration at Visby, Gotland.



The history of HVDC Part 1: The mercury arc valve era

Lennart Haglöf joined the Company in 1954 and came to the HVDC operation in 1962. When leaving in 1987 to join the Group Management Staff he had held several management positions and been intimately involved in design, installation and commissioning of a number of HVDC projects, including Sakuma in Japan, Pacific Intertie in the U.S. and Itaipu in Brazil.



The history of HVDC Part 2: ASEA's HVDC Thyristor Introduction 1965 - 1980

Per Danfors was active in HVDC from 1960 to 1980. During this period he experienced inside knowledge of the mercury arc era, having spent 7 years in the 60's with the Pacific Intertie ASEA - GE Joint venture project from concept to commissioning. In the 70's he was then involved in ASEA's launching of the thyristor era up to and including the Itaipu HVDC Project.



The history of HVDC Part 1: The mercury arc valve era

HVDC 50 years: Presentation at the Gotland seminar 2004-05-06

by Lennart Haglöf

Ladies and Gentlemen!

We are celebrating today the 50-year anniversary of the commercial application of a brand new technology. Indeed, in 1954 it was so new that nobody could really guarantee its performance.

1954 is also the year when I joined Asea as a trainee engineer and I am pleased and honored to have this opportunity to tell you about some of the important steps in this history.

Sweden in the 1950's was a fertile ground for transmission development. Electric energy consumption doubled each decade, with the major hydro reserves in the north, some 1000 kilometers from the major load centers in the south. It was clear that a major new transmission facility from the North would be needed in 1952.

The choice was between going from 230 to 400 kV AC or introduce a completely new technology, High Voltage Direct Current, HVDC. When the decision had to be made in the late forties the HVDC alternative was not yet ripe for such a major backbone transmission case.

Thus, in 1952 the World's first 400 kV AC transmission was commissioned. For the first application of commercial HVDC some other place had to be found. And this place turned out to be Gotland.

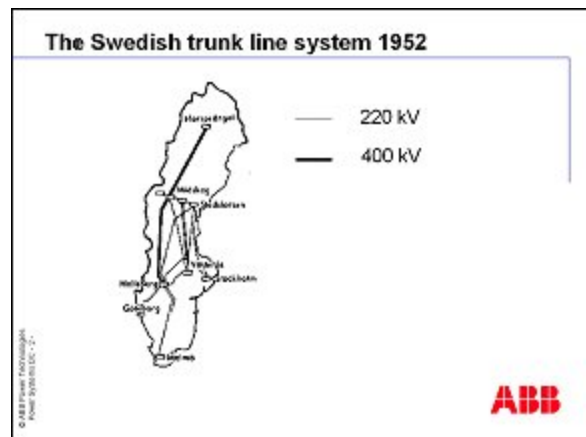
Gotland was the only part of Sweden, which completely lacked hydro resources, and it was too far out in the Baltic to have an AC connection to the Swedish mainland. The island was supplied by a single steam power plant and the electricity rates were considerably higher than on the mainland.

We were lucky to have in Gotland a consumer of moderate size with a power system owner who was open to new solutions. But even for this size, some 20 MW, major development efforts were required, on, for example, the system layout and design, a high-voltage converter valve, other main circuit components, control systems and a 100 kV submarine cable.

And the first step in 1954 was followed by several others, some of them also of pioneering nature. Since they belong to the thyristor era, I leave it to Per Danfors to comment on them.

Several development groups were involved in early DC transmission trials or devices for AC/DC conversion. Some used mechanical contact devices, others static components such as mercury arc valves or gas filled vacuum tubes (thyatrones).

A well-known trial DC system was built by Rene Thury. He used series connected rotating machines to produce DC voltages of up to 125 kV. Parts of the system were in operation well into the 1930's but it apparently did not meet cost and reliability criteria. It never reached the commercial application level.



Gotland – HVDC milestones

1954	Stage I: The first commercial HVDC transmission, 20 MW, 100 kV
1967	The first HVDC thyristor test valve
1970	Thyristor converter added, 30 MW, 150 kV
1983	Stage II, 130 MW, 150 kV
1986	Stage I retired to give space for Stage III
1987	Stage III, 130 MW, 150 kV
1999	The first commercial HVDC Light transmission, 50 MW, ± 80 kV

© ABB Power Technologies
1999-2004-05-06

ABB

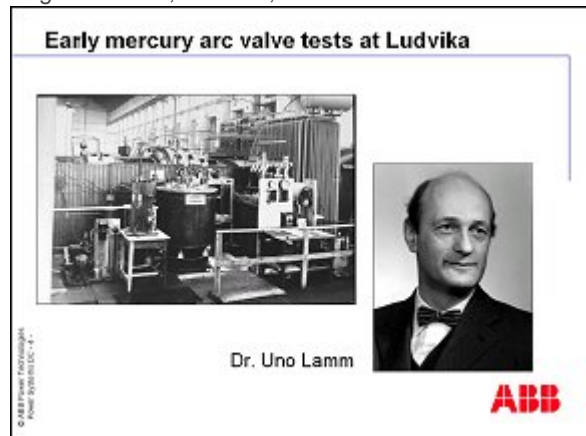


I am here bypassing most of this interesting history and moving to Ludvika, Sweden, in 1928.

ASEA had decided to take up manufacturing of mercury arc rectifier valves, a product used by many industrial customers. Brown Boveri, by the way, had a leading position in this business.

The first valve did not work properly - it suffered so-called arc-backs - and a young engineer fresh from university and military service, Uno Lamm, was asked by the plant manager to look at the piece and fix it.

This proved to be his fate. When he retired in 1969 the problem was still not completely solved but in the process Lamm had become "the Father of HVDC".



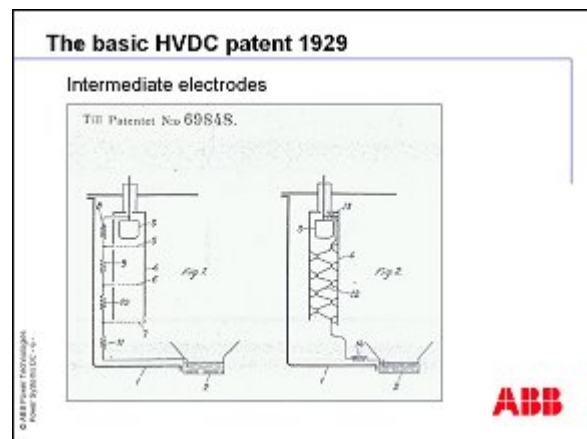
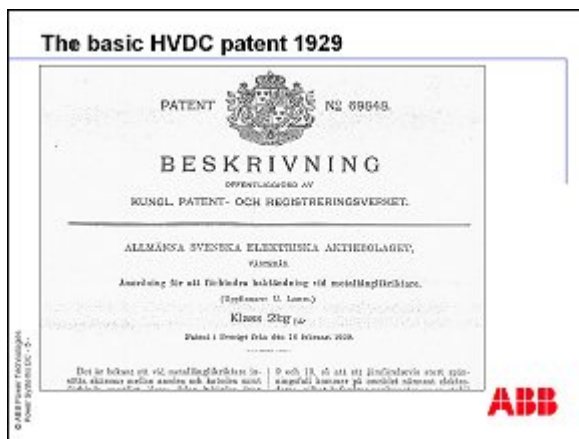
And what about the arc-backs? Well, it proved possible to

- reduce the frequency drastically and
- design the system so it could live with an occasional arc-back

From the very beginning it was obvious that high voltage was a major challenge.

ASEA fairly soon could market rectifiers for industrial plants, that is for a few kilovolts, but for transmission over any appreciable distance this was of course way too low.

Back to Uno Lamm: He had seen the problem and already in 1929 got a patent on a "device to prohibit arc-backs in metal vapor rectifiers". From then on, the development towards really high voltages built on his idea of a number of intermediate electrodes connected to an external voltage divider.



The solution appeared very simple on paper, but many design problems remained to be solved, such as shape of the electrodes, choice of materials, processing techniques etc.

It gradually became obvious that this was an empirical science, valve behavior had to be tested in long-term, full scale testing. The relatively weak network in Ludvika became severely stressed by short circuits (caused by arc-backs) and harmonics. If the tests went well, a white cloud rose from the water resistors used to absorb the energy, and if not the lights all over the city blinked.

We are now approaching the mid-30's and other technologies than the mercury arc valve were still pursued. In Sweden, the well known inventor of the absorption type refrigerator, Baltzar von Platen, worked on a mechanical contact device, driven by a synchronous motor (the Glesum Project). The Ludvika group considered him a serious competitor who could jeopardize continued support for the mercury arc alternative. But von Platen had some bad luck. On the very day when his work was presented at a meeting of a Swedish engineering society, ASEA's Uno Lamm managed to steal the show. His development group had just completed work on a mercury arc valve for 25 kV, some 10 times the operating voltage of existing valves for industrial use, and tests were planned to start the



same day. Before the speech Lamm telephoned Ludvika and was informed that tests had just commenced on the new valve and that it was operating beautifully. Lamm's announcement and his forceful arguments in favor of the mercury arc technology got all the attention and headlines in the press afterwards. When the valve gave up after 20 minutes of operation the Ludvika engineers did not care - or dare - to call Lamm.

Good timing can be of real importance also in development work.

The tedious work towards usable high voltage valves was sometimes accompanied by bold visions. In 1938, for example, an American study presented a scheme to transmit large amounts of power from the Grand Coulee and Bonneville dams in the western USA to the New York area, a distance of 3500 km. The transmission voltage was expected to be in the range of 350 - 750 kV, and would be achieved by thyratrones (a kind of vacuum tube), which at that time were made for up to 30 kV.

It would take 32 years before an HVDC transmission was built from the Bonneville dam to Los Angeles, a more modest 1300 km, but the longest in the world at that time. And using mercury arc valves.

In this case as well as others, our major customers made an important contribution, by participating in testing or installing, on normal commercial terms, first generation equipment and thereby taking certain operational risks.

Still, the very active involvement by the Swedish State Power Board (SSPB) (now Vattenfall AB) in high voltage transmission development is probably unique.

The SSPB saw the potential in HVDC very early and in 1943 an agreement was reached to build a full-scale valve laboratory at Trollhättan. Vattenfall contributed the appreciable amounts of power required for the full-scale tests as well as operation personnel. The limitations by the comparatively weak power system in Ludvika were thereby eliminated.

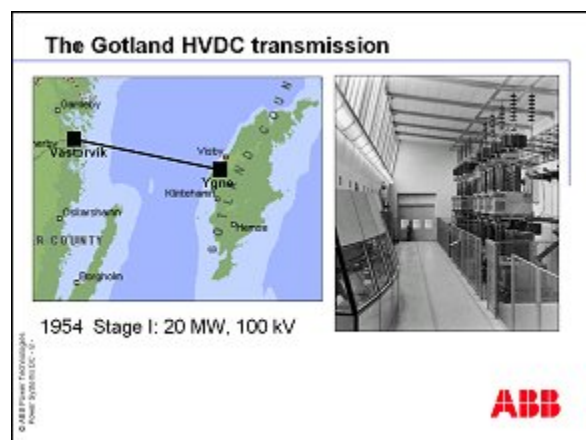
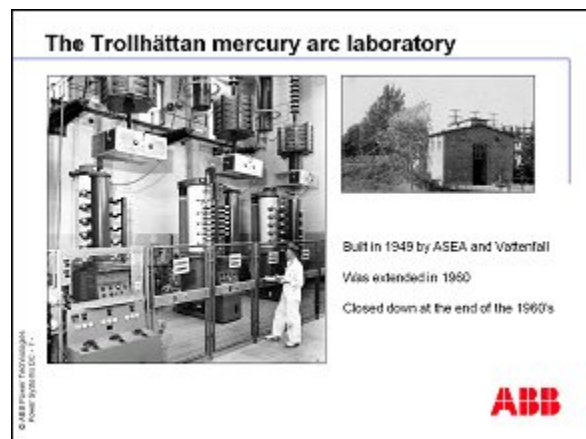
For real transmission tests over a distance of 50 km, at 6.5 MW and 90 kV, a line and another station at Mellerud were also made available. Vattenfall's Director General at the time, Waldemar Borgquist, took a strong personal interest in the HVDC development, even after HVAC was chosen for the 400 kV North-South transmission system in Sweden. He personally chaired the joint meetings following up on progress in the Trollhättan laboratory and HVDC development work in general.

Thus, a proposal to build an HVDC transmission to Gotland was favorably received and in 1950 Vattenfall and the Swedish Parliament decided to go ahead. Following this decision, a contract for a 20 MW transmission including a 100 kV DC cable was placed. At 20 MW and 100 kV, the scheme can be said to be "half scale", presenting a reasonable risk level for both the owner/operators and the suppliers.

The contract was of course a great stimulus -and challenge- for the team in Ludvika. 23 years had passed since Lamm got his patent, and now was the time to show results!

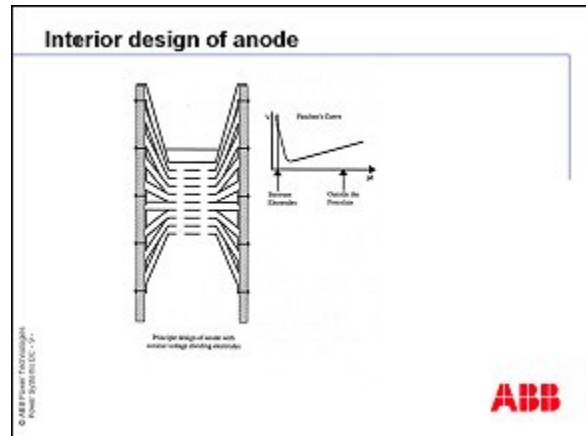
But the development and design work was still rather far from completed. Valve designs were tested continuously. When the design had to be frozen, some 140 different variants had been tested full scale. The task of analyzing and interpreting the maze of data produced by these tests fell on Birger Funke and his small team. They really learned the meaning of "empirical".

Very critical for valve performance and thus one of the well-kept secrets of interior design was the shape of the grading electrodes.

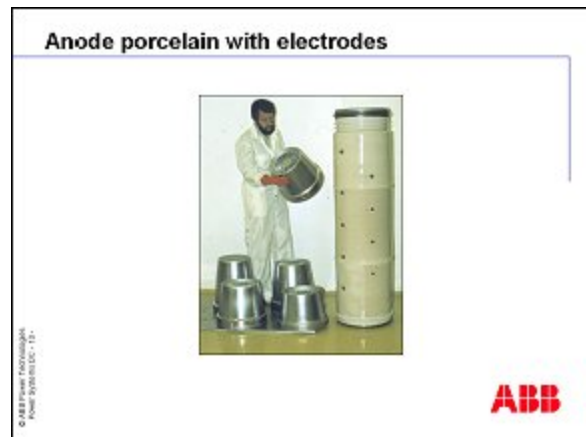




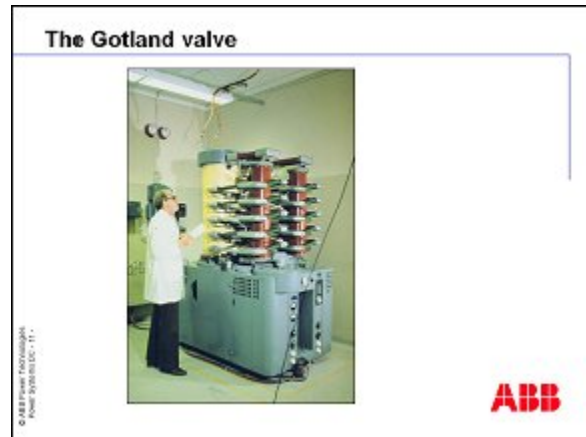
The slide shows how bucket-like electrodes are mounted inside a porcelain cylinder. Different laws are determining voltage withstand on the outside and the inside respectively, which accounts for the perhaps unexpected shape.



In real life it looked like this. The slide shows the final development step of an anode porcelain and intermediate electrodes. Six such anodes were connected in parallel to carry a line current of 2000 A.

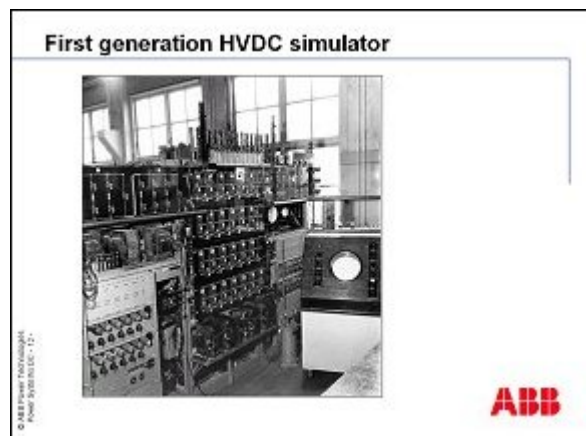


And finally, the complete Gotland valve, as installed and after some modifications made to the external voltage divider.



But the DC system is more than the valve, however critical or important it might be. There was practically no established know-how on main circuit systems, special equipment requirements, control strategies or risks for disturbances to other infrastructure. The mathematical groundwork for this was to a large extent laid by Dr. Erich Uhlmann, but verifications were needed.

Early experiences, e.g. from the Trollhättan - Mellerud tests, showed that control properties and requirements could be tested out in low power simulators. The slide shows the first simulator, to be succeeded by many generations of simulators and an increasing reliance on computer software.





A real first in Gotland was also the use of electronics - at that time vacuum tubes etc. - for on-line control of the whole transmission process. The required reliability was obtained through careful selection of components, conservative design and judicious use of redundancy.

A very important innovation resulting from this system development work was the use of a by-pass valve connected across the six-pulse converter bridge. The by-pass valve made it possible to live with a limited number of arc-backs. An "arc-back suppression unit" detected the arc-back current and immediately blocked the main valves and deblocked the by-pass valve. Normally, the faulty valve recovered very quickly, the main valves were deblocked again within a second, and the power system hardly noticed the disturbance.

Today we can see that the system design from 1954 has stood the test of time very well. It took until the 1990's before any major new solutions - such as Capacitor Commutated Converters - were introduced. Gotland I also had a very complete control system, including frequency control of the island power system.

One area of system design which could not be completely determined by theoretical investigations was the possibilities of using the earth as return path for the DC current, the risk for corrosion on grounded objects or disturbances to other utilities, for example telephones, railway signalling, etc.

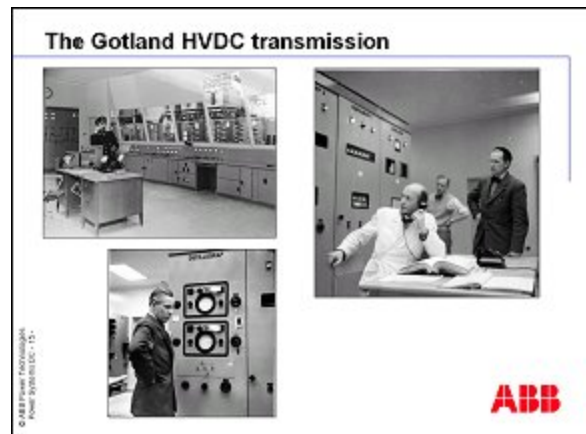
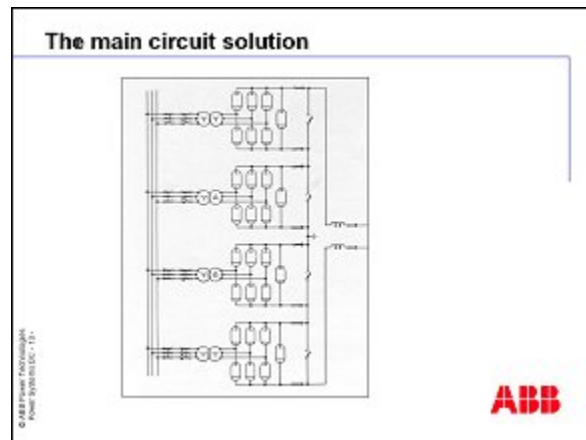
In a rare demonstration of flexibility and cooperative spirit a unique test was arranged one night.

From a DC source in Gothenburg current was fed through a specially established line up to Kiruna in the North, where an electrode was placed in a mine. For a short period, no trains were moving and telephones did not work. It was "the night when Sweden stood still". Measurements were made on stray currents, disturbances etc. and much valuable information was obtained. For example, it was shown that the current disappeared into the earth within a very short distance from the electrode, which meant that monopolar transmission was indeed possible.

Lamm was personally leading the commissioning team to a successful start-up. True, there were disturbances in the beginning, but after the modification of the external voltage divider on the valves and some other measures, the disturbance rate became quite acceptable.

However, when after the official inauguration the participants sat down for dinner in Visby, the lights went out. Lamm later said that it was somewhat embarrassing to see the speed by which the waiters produced a large number of candles. Apparently they had learned to be prepared.

But disturbance rates did go down and Gotland enjoyed a much better frequency stability when control went from the steam power station to the HVDC link. In 1955 Lamm moved on to a broader assignment and was succeeded by Gunnar Engström, who inherited the task given to Lamm in 1928, that of fixing the arc-backs.





Engström led the Converter Department through the rest of the 50's and most of the 60's, a period of varied challenges. First, surviving until the next HVDC project, then managing the tremendous expansion when the commercial break-through came in the early 60's. And, as rating requirements went up, the mercury arc valves continued to be a technical challenge.

In 1967, Engström became GM of the Electronics Sector, which also included responsibility for the development of thyristors, the next key component for HVDC systems.

It took quite some time before the next contract was placed, for an HVDC cable transmission under the English Channel. Power rating was 160 MW and cable voltage 100 kV. The scheme was justified by the difference in time for the daily power peaks in the English and French networks respectively.

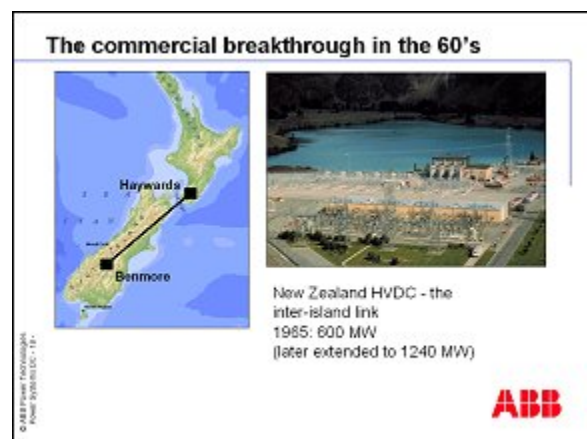
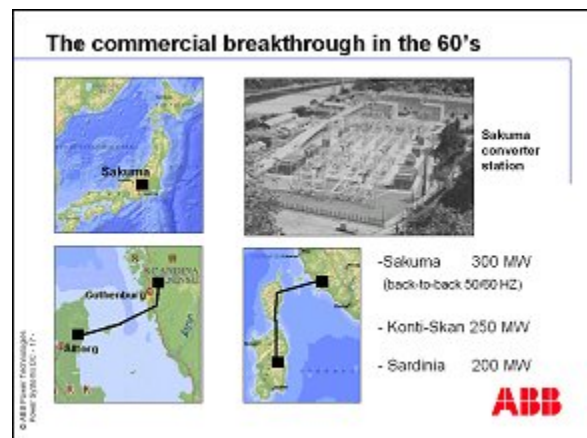
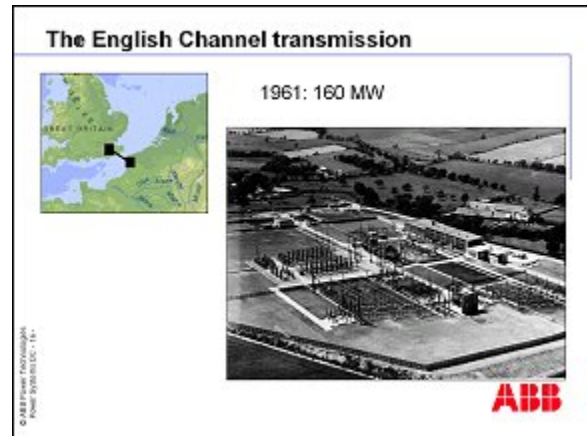
Then came in the 1960's the commercial break-through for HVDC, with simultaneous work on 4 schemes:

Konti-Skan linked the Nordic system with Western Europe primarily to sell surplus hydro energy to Denmark and Germany and to provide peak support to the Nordic system when needed.

Sardinia-Italy utilized coal resources on Sardinia and delivered energy to the Italian mainland.

Sakuma, Japan, the first HVDC frequency converter, connected the 50 and 60 Hz systems in Japan, to some extent for energy exchange but primarily to provide emergency support at disturbances in either network. Provided the networks could take it, the station was able to reverse from 300 MW in one direction to 300 MW in the other in 0.2 secs. By having this feature, spinning reserves in both networks could be reduced considerably.

In **New Zealand** at the same time a 600 MW transmission was built from new hydro developments on the Southern island to Haywards close to Wellington on the Northern island. The scheme boasted several new features: the first long (580 km) HVDC overhead line, combined with cables under Cook Strait (known for its strong currents), ground return with both sea and land electrodes, measures to reduce impact from earthquake stresses, etc.

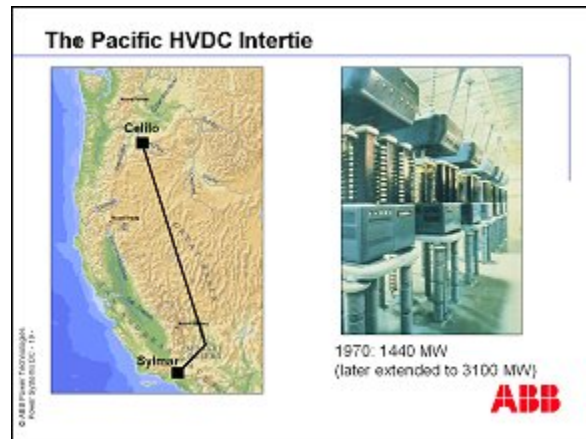




The final step in ratings for the mercury arc valves was taken in North America:

- 150 kV bridge voltage and 2000 A in Nelson River, Canada, and
- 133 kV/1800 A in the Pacific Northwest-Southwest HVDC Intertie in the U.S.

At 1300 km, the **Pacific Intertie** was the then longest power transmission in the World. And like the Gotland cable in its day, it proved possible to upgrade the HVDC line in voltage as well as current, to achieve a final rating of 3100 MW at +/- 500 kV. But these upgrades belong to the thyristor era.





The history of HVDC Part 2: ASEA's HVDC Thyristor Introduction 1965 – 1980

HVDC 50 years: Presentation at the Gotland seminar 2004-05-06

by Per Danfors

Ladies and Gentlemen!

By the end of the 60's, ASEA had a very impressive reference list of important HVDC installations around the world that were all performing very well. In addition ASEA's licensee English Electric had also several large HVDC references operating with mercury arc valves. Together there was over 5000 MW of Mercury arc HVDC installations operating or under construction around the world. HVDC was now an accepted transmission technology and the market for both cable and long distance transmission using HVDC was growing. Up until this time ASEA was alone in this market with the mercury arc valve. This component was now proven for HVDC converters, it was inexpensive to manufacture, had low losses and was of robust design, especially in rated current.

Mercury arc valve HVDC

By 1970:

- there was over **5000 MW** of HVDC Transmission in commercial operation or under construction around the world
- HVDC was an accepted electric transmission alternative and the market was growing
- the Mercury Arc Valve was a proven component for HVDC converters:
 - Inexpensive to manufacture
 - Low losses
 - Robust design

ABB

Thyristor valve HVDC

But:
in the middle of the 60's an alternative technology for HVDC converters emerged:

The Thyristor

ABB

The thyristor



The thyristor also had impressive advantages:

- Very Reliable
- Fail Safe failure mode
- Compact Design

ABB

Obviously ASEA's competitors wanted to get a share of the HVDC business, and their opportunity presented itself as a new component, the thyristor, started to emerge in the middle of the 60's. The thyristor had proven to be very successful in industrial applications. Thyristors are reliable elements, they do not age and if they fail, they fail safe, losing their semi-conductor properties but maintaining their current carrying capability. And they could offer compact converter designs

The development of high power thyristors was encouraging. By series and parallel connecting individual thyristors any converter rating was basically possible. In 1967, GE, ASEA's partner in the Pacific Intertie, offered a thyristor alternative for an option for a second transmission to Mead which was never materialized. And in 1969 the German HVDC Consortium received the first order for a thyristor based HVDC transmission in Southern Africa. ASEA was for the first time faced with a real competitive market. Mercury Arc technology was no longer unique for HVDC transmission systems.



ASEA's management was well aware of these developments in the middle of the 60's, and questioned the HVDC Team periodically regarding the competitiveness of Mercury- as compared to Thyristor-based systems. Here is a typical example of a paradigm shift in technology where those who were involved with the old technology were reluctant to see the advantages with the new thyristor technology. Luckily ASEA's management realized this and organized an independent parallel engineering team with the job of developing a new thyristor valve completely separate from the Mercury arc team.

In a very short time this new team had installed a thyristor test valve 1967 in Gotland which functioned very well, and in 1970 the first commercial thyristor converter group was operating in series with the two original mercury arc groups in the Gotland HVDC Transmission - the first of its kind in the world. With the support of Vattenfall AB the Gotland HVDC transmission proved to be the testing ground for yet another world record - and more records were to come.

In 1971 ASEA decided to discontinue all further development of mercury arc valves.

This was the start of ASEA's continued market leadership in HVDC transmission, although now there were some 4 potential competitors around the world in Europe, the US and Japan. ASEA was not new to this new technology. The company had vast experience in industrial applications of thyristors in motor control and locomotives, and was the leading manufacturer of thyristors in Europe at this time. In addition, ASEA had the advantage of very close cooperation inside the Company between the HVDC system designers and the thyristor component designers.

A Paradigm Shift

ASEA had a dilemma:

The choice between:

- Mercury Arc or
- Thyristor based converters

From 1965, ASEA developed both technologies independently in parallel.

By 1970 ASEA had the world's first commercial thyristor based HVDC converter in operation in the Gotland scheme.



The Gotland HVDC transmission



1954 Stage I: 20 MW, 100 kV (mercury arc valves)

1967 Thyristor test valve

1970 Thyristor converter added,
+10 MW, 150 kV



Thyristor valves for HVDC

ASEA was not new to Thyristors:

- ASEA had 10 years experience in:
 - Industrial Drives
 - Locomotives
- ASEA was Europe's largest supplier of industrial thyristors



Thyristor valves for HVDC

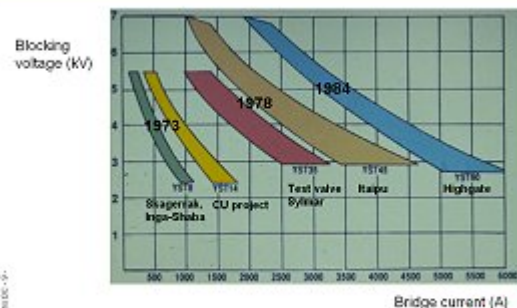
With the growing market for HVDC ASEA started development of a single string of

- high power,
- high voltage
HVDC thyristors

Competitors focused on using industrial thyristors connected in series and parallel

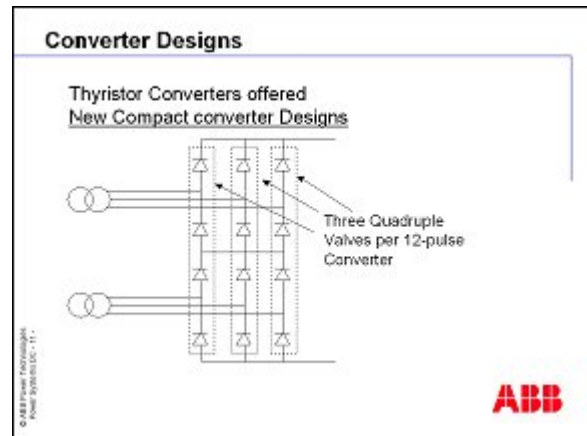
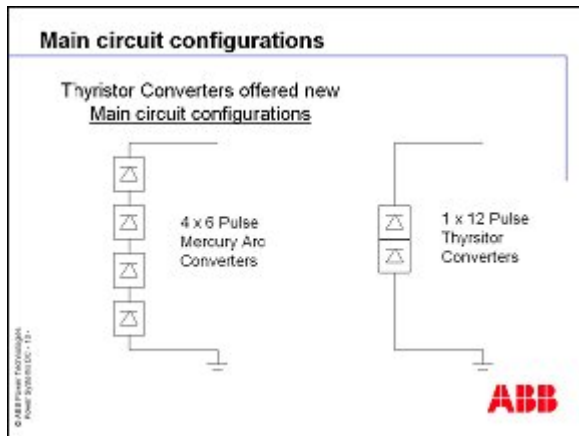


Early thyristor data for HVDC

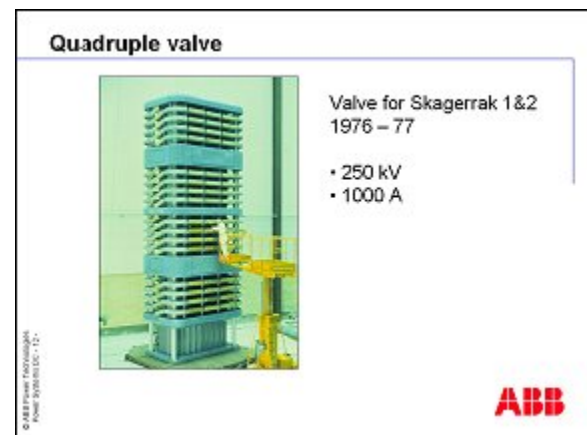




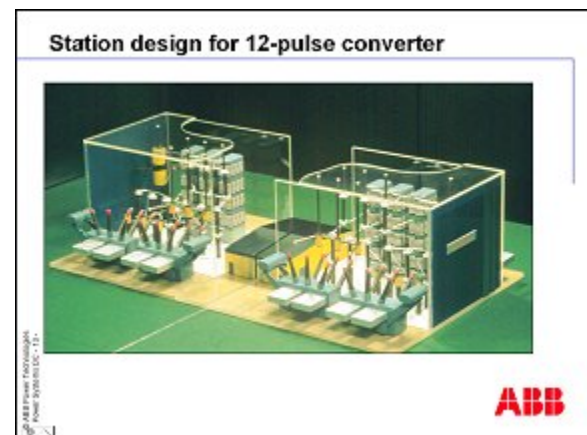
As HVDC became a new market opportunity, the company started to develop high voltage high power capability for HVDC. ASEA chose to develop HVDC thyristors for maximum power capability and series connection of a single string of series connected thyristors to reduce costs. Other competitors focused initially on using industrial thyristors to reduce costs and adapted current ratings by parallel connection of selected thyristors.



Now that ASEA had chosen a thyristor based HVDC system, a number of new options presented themselves that would make the total design more efficient for HVDC transmission. Mercury arc valves had reached a voltage limit of 125-150 kV per 6-pulse group. This meant that converter groups had to be connected in series, and up to 4 such mercury arc groups per pole have been built for a line voltage of ± 500 kV. But as the thyristor elements proved very reliable, designs were developed to use only one 12-pulse converters per pole for full voltage. The Inga Shaba project for instance has one 500 kV 12 pulse converter per pole.



This also resulted in practical arrangements of the transformers with the secondary bushings penetrating the valve hall with indoor design of the bushing insulators, a clear improvement and very compact layout.







Valve cooling concepts

ASEA's initial HVDC thyristor converter designs utilized air cooling, even though ASEA had ample experience of water cooling for mercury arc valves.

ASEA switched over to water cooling when the market required larger currents and larger thyristors became available.




air cooled




water cooled


© ABB Power Technologies
Power 2020/01/01 - 18+



Valve cooling concepts




Module replacement in air cooled thyristor valve



Thyristor replacement in water cooled thyristor valve

© ABB Power Technologies
Power 2020/01/01 - 15+




The first ASEA thyristor converters were air-cooled. Even though there was a lot of know-how in water-cooling for mercury arc valves, ASEA did not adopt this cooling method until later during the 70's. It was the German HVDC consortium that first demonstrated the efficiency of water-cooling in the Nelson River Project at the end of the 70's. This prompted ASEA following suite.

Coordinated HVDC development with customers

- 1967 Gotland: The first HVDC thyristor test valve in parallel with a mercury arc valve
- 1970 Gotland: Thyristor converter added: +10 MW.
- 1973 New test valve installed in Konti-Skan (Vester Hassing)
135 kV, 1,050 A (air cooled)
- 1978 New test valve installed in Pacific Intertie (Sylmar)
133 kV, 2,000 A (water cooled)

© ABB Power Technologies
Power 2020/01/01 - 18+




The Gotland HVDC Transmission

The Gotland HVDC Transmission has been ABB's testing ground for State-of-the-art HVDC technologies:

- Converters
- Control Equipment
- Main Circuits


© ABB Power Technologies
Power 2020/01/01 - 17+




ASEA continued to cooperate with End Users and installed an air cooled test valve in the Konti Skan transmission which offered excellent opportunities to monitor performance and gain feedback from the end users that were invaluable in the design of the valve. A few years later a water-cooled test valve was installed in the Sylmar terminal of the Pacific Intertie.


Second generation test valve

1973 Konti-Skan / Vester Hassing 135 kV, 1,050 A
YST 8, YST 14 (air cooled)







© ABB Power Technologies
Power 2020/01/01 - 18+




Third generation test valve

1978 Pacific Intertie / Sylmar
133 kV, 2,000 A
YST 35, YST 45 (water cooled)



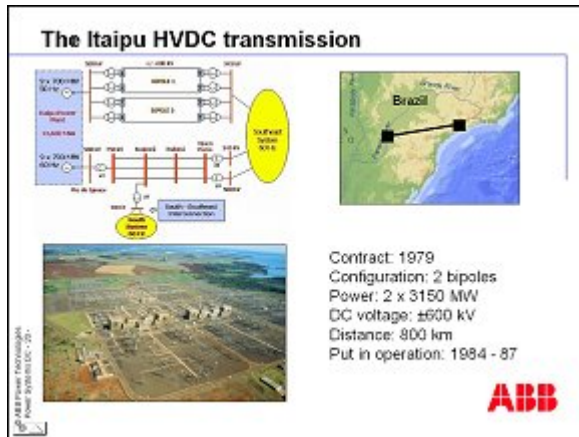


© ABB Power Technologies
Power 2020/01/01 - 18+





Initially, customers often questioned the reliability of the first thyristor valve designs. The solution was rather simple, namely to add more thyristors in series as redundancy, thus reducing the nominal stresses on all the series connected thyristors. In a way you could say that these redundant thyristors were the spares required for maintenance. As experience was gained, the number of redundant thyristors could be reduced appreciably. Today HVDC Installations have shown excellent records of reliable operation and forced outage rates are low. A consequence of this is the increased power ratings of 12 pulse converters.



HVDC thyristor references	
At the start of the 1980's the HVDC thyristor reference had added over	10,000 MW
In Itaipu (1984 – 87) ABB supplied 12-pulse converters for	780 MW
By the turn of the century ABB supplied 12-pulse converters for (Three Gorges, China and Pacific Intertie / Sylmar, USA)	1500 MW

ABB

The developments in the 70's are impressive. The last mercury arc converters had a 12-pulse rating of about 500 MW, whereas the Itaipu thyristor 12-pulse converters have a rating of over 780 MW. And the size continued to increase to today's 1500 MW ratings for 12 pulse converters in the Chinese HVDC transmission schemes delivered by ABB.

With this summary of the change from mercury arc to thyristor technology, I would now like to hand the word to Gunnar Asplund who will tell you about the exciting continuation of the semiconductor based converters and future prospects.