

dc power transmission

mercury-arc to thyristor HVdc valves

“FORTUNATELY, THE TECHNOLOGY of employing thyristors for dc transmission differs more in dimensions than in principles from that of employing mercury-arc valves.”

E.W. Kimbark

Introduction

Direct current (dc) power transmission first came into existence in France through the contribution of Marcel Deprez that was showcased in the Paris Exposition in 1881. In 1882, Deprez helped Oskar Von Miller (founder of AEG in Germany) to design long-distance dc transmission to carry 15-kW power at a voltage of 2,000 V over a distance of 35 mi (56.3 km) from Miesbach, Germany, at the foothills of the Alps to the Glaspalast in Munich. The rise and fall in the use of dc power transmission in the beginning of the 20th century followed by its reemergence in the early 1950s is quite interesting. Between 1900 and 1950, there was not a moment when dc systems of one type or another were not working or under development. The dc option for power transmission was never abandoned, due to the tenacity of a few men like René Thury, who felt that two wires were better than three and reactance was an unnecessary burden.

DC was directly generated and transmitted to load centers. To enhance dc power transmission capability, Swiss

The “History” article in this issue of *IEEE Power & Energy Magazine*, authored by Deepak Tiku, is particularly timely in that it continues the story told in the September/October and November/December 2013 columns. The earlier two-part article covered the synchronous or rotary converter, an early electromechanical means to convert alternating current (ac) power to direct current (dc) power for many needed applications. The rotary converter was invented in the latter years of the 19th century and was widely used during the 20th century. However, beginning in the 1930s, rotary converters were gradually supplanted by newer technology.

This article discusses that newer technology, beginning with the mercury-arc valve and converter, which was invented in 1901 and progressively improved such that it enjoyed widespread use by the 1930s. The development of the high-voltage (HV), high-power, mercury-arc valve led to HVdc transmission projects in a number of countries. The advent of solid-state electronics and the silicon-controlled rectifier in the 1950s resulted in the development of the thyristor valve converter that began replacing mercury-arc converters during the 1960s. Today, the field belongs to the thyristor, and both rotary and mercury-arc converters have become virtually extinct.

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We are pleased to welcome Deepak Tiku as our guest history author for this issue of *IEEE Power & Energy Magazine*.

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engineer Thury pioneered what became known as the “Thury system” in 1890, using the series connection of dc generators. However, the exploitation of dc transmission had to wait until the development of the high-voltage, high-power, mercury-arc valve in the 1940s. Since then, there has been no looking back; mercury-arc valve bridges with power-handling capability as high as 270 MW were developed for high-voltage dc (HVdc) transmission in the 1960s. A decade later during the 1970s, thyristor valves completely replaced mercury-arc valves due to their ruggedness, reliability, low maintenance, and cost and gave real impetus to dc power transmission.

AC Versus DC

Initially, power systems were developed as isolated networks looking after local needs. But as the demand for power and transmission distances grew, voltages had to be raised, and networks required interconnection for reliability. DC systems were constrained due to the problems of commutation and nonavailability of equipment for voltage transformation and interruption of currents. Further, Tesla’s invention of the induction motor revolutionized the utilization of alternating current (ac) power in industry. This led to the dominance of ac over dc for generation, transmission, and to a large extent the utilization of power. In spite of all this, dc was used for drives (for example, for city railways and rolling mills that required better controls) and for electrochemical processes. The dc transmission could not be realized without a sizable loss of power. The solution was to generate ac power, transmit it at higher voltages, and convert it to the desired dc voltage level when required. Rotary converters were the only means available for conversion from ac to dc. The rotary converters invariably fed loads of varying nature, which was highly inefficient.

Networks of 220-kV ac systems were established in the 1920s. As the ac systems expanded, stability problems were encountered. DC transmission systems were considered to be the best solution. But because the necessary equipment to generate HVdc was not available, it continued to remain in the background. At that time, the only dc system that existed was the Thury system. It used low-speed dc machines driven by water turbines, generating over 3,000 V. The low speed was essential for satisfactory commutation and could not be used for thermal power stations having high-speed turbines. The dc generators would run in series and supply a fixed current to the load consisting of series-connected dc motors driving loads directly or, alternatively, using motor-generator sets to supply electricity. Many such systems existed in Europe from 1890 onwards; the first one was the 630-kW, 14-kV, 37-mi (59.5-km) system in Genoa, Italy. The most important dc system based on the Thury system was the 150-kV, 20-MW Moutiers-Lyon system in France that remained in service for many years from 1906 to 1937. The Willesdon-Ironbridge system was installed in

England in 1910 to supply power at 10 MW to Southall 5.5 mi (8.85 km) away until it was dismantled in 1924. The Thury system proved inadequate for higher power ratings.

Simultaneously, a search was going on for achieving conversion at high voltages as the direct generation of the Thury system had limitations. The theory for converters was well developed before World War I, and a patent was filed by an American, P.H. Thomas, in 1903. Contrary to the advanced state of electrical theory, converter technology was in a primitive state. In a converter, there is no conversion of energy as in the case of rotary converters. With the advent of the mercury-arc rectifier, conversion from ac to dc took

place directly through periodic switching. The efficiency of these rectifiers was high and practically the same under all

operating conditions. The additional advantage of simplicity and rapid starting contributed to their popularity. All major requirements of power rectification from the late 1920s to the 1950s were met by mercury-arc rectifiers.

By the time HVdc transmission was technically feasible with the availability of high-power mercury-arc valves,

the stability problems in ac systems were more or less overcome. Hence, dc had to compete with ac in economic terms as well. An overhead transmission distance of at least 500 mi (~800 km) was necessary to create significant incentive

to proceed with HVdc. Also, over the years the requirement of power systems changed. DC transmission was not to connect dc source to dc load; instead it had to connect power systems which carried ac currents.

The mercury-arc valve was invented in 1901 by Peter Cooper Hewitt of the United States.

Mercury-Arc Valve Development

The mercury-arc valve was invented in 1901 by Peter Cooper Hewitt of the United States. By the end of World War I, the glass bulb (or Hewittic) mercury-arc rectifier reached its operational limit due to the large size of the required glass envelope. The steel tank rectifier, having robust construction and a greater current-carrying capacity, was also developed first by Hewitt in 1908. Because of the better heat conduction of steel, the large cooling dome of glass-bulb-type rectifiers was not required. In the late 1920s, Langmuir invented grid control, which made it

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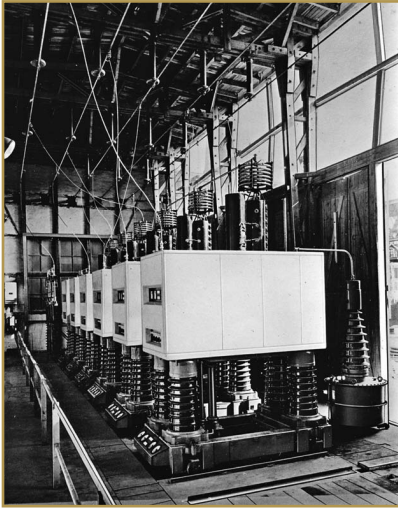


figure 1. Six single-anode mercury-arc valves at Charlottenburg Station, Berlin, for the HVdc test installation, Berlin-Moabit, 1942 (photo courtesy of Siemens AG, Siemens Press Picture, ref. number s0sep200501-01).

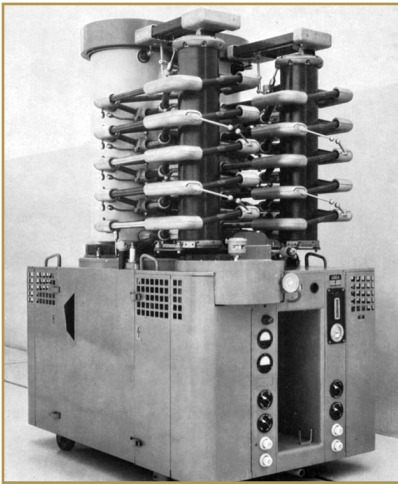


figure 2. A mercury-arc valve for the Gotland HVdc link; from ASEA Brochure 8585E, 1971 (photo courtesy of ABB Asea Brown Boveri Ltd., Zürich, Switzerland).

possible to have both rectification and inversion processes. The main difficulty in steel tank rectifiers was the maintenance of vacuum-tight seals required to maintain voltage blocking capability during negative anode voltage.

These limitations encouraged the development of conversion by other means, e.g., periodic switching of moving contacts of the generator with the help of a synchronous motor. This

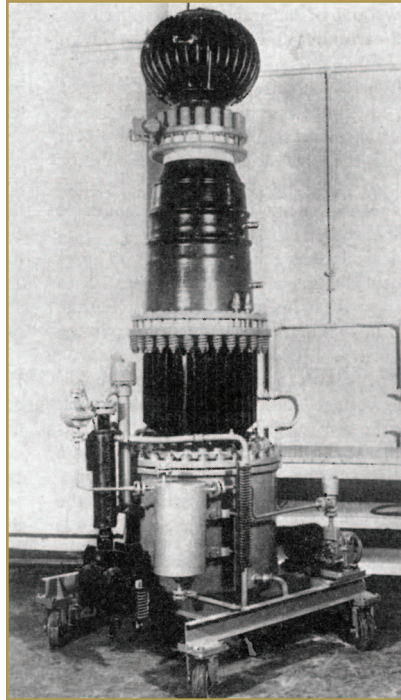


figure 3. A single-anode mercury-arc valve, Volgograd-Donbass HVdc system (130 kV, 900 A). The valve is 11.5 ft (3.5 m) high and weighs approximately 2 tons (photo courtesy of the IEEE).

principle was used by Calverley and Highfield in England in developing the transverter system in the early 1920s and the Glesum system in Sweden in the early 1930s. Such a system could not operate satisfactorily under transient conditions. Marx air-blast rectifiers generated some hope in the 1930s, but it was short lived because of failures at higher duty. It was obvious that switching must be carried out by electronic valves that have the inherent capability of opening the circuit or blocking when the current reached zero.

Due to continuing improvements, by the mid 1930s, mercury-arc rectifiers were available in many designs, broadly classified under two categories: 1) sealed glass envelope for smaller ratings and 2) steel tanks with metal cooling jackets and vacuum pumps for larger ratings. In 1932, the mercury-arc valve was first used for an experimental 3-MW, 45-kV dc link between Switzerland and Germany. However, it was difficult to achieve HV withstand capability and low losses that would

make it economical and competitive with ac transmission. In HV mercury-arc valves, the blocking voltage was concentrated into a narrow region that made these devices highly sensitive to surface contamination and vacuum conditions. In 1939, Dr. Uno Lamn of ASEA was granted a patent for the introduction of grading electrodes in mercury-arc valves. It improved voltage distribution and the withstand capability considerably. Following this, dc transmission was taken seriously and high-power experimental links came into existence in Germany from Moabit to Berlin (see Figure 1), in Sweden, and in the United States in the 1940s. However, work on dc transmission was largely slowed down because of World War II.

In 1941, the first commercial HVdc transmission system was ordered in Germany from the consortium of Siemens-Schuckert, AEG, and F&G. When commissioned, it would transmit 60 MW of power at ± 200 kV from the Vockerode generating station on the river Elbe to Berlin over a distance of 71.5 mi (115 km) overland through a pair of buried cables to avoid attracting the attention of allied forces. Each converter station had two 200-kV, six-pulse

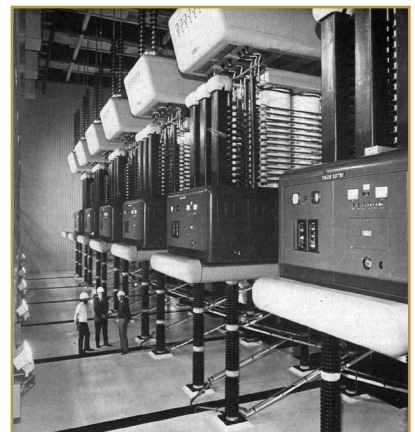


figure 4. English Electric Co. mercury-arc valves at Dorsey Station, Nelson River 1 project, Manitoba, Canada [from J. M. Ferguson, "Corridors of power," *Proc. Inst. Elec. Electron.*, vol. 120, no. 1, Jan. 1973, p. 49, photo courtesy of the Institution of Engineering and Technology (IET)].

bridges, and each valve in the bridge was made up of three series-connected, single-anode mercury-arc valves. The Germans completed the ambitious Elbe-Berlin HVdc project in April 1945 under the backdrop of World War II but commissioning activities could not be concluded. After the end of the war, the entire system was disassembled and moved to the USSR by Russians, preventing Germany from achieving the feat of commissioning the first commercial HVdc project. The Elbe-Berlin HVdc system was reinstalled in 1950 as the Moscow-Kashira transmission system, which was used as a power transmission link and research facility.

Since then, several mercury-arc-valve-based HVdc systems were commissioned. In 1946, ASEA energized

a 37.3-mi (60-km) experimental dc line between Mellerud and Trollhättan in Sweden. The power capability of the link was 6.5 MW at 90 kV. Subsequently in 1954, the first commercial HVdc submarine Gotland link (20 MW, 100 kV) was commissioned by ASEA (see Figure 2). As HVdc mercury-arc valve technology matured, two distinctively different valve designs, Swedish and Russian, were in use. The major difference was due to the number of grading electrodes. The Russian valve used four grading electrodes whereas the Swedish design used a large number of grading electrodes, for example, 20 electrodes for a 125-kV valve.

The few grading electrode designs offered a high current rating/anode but a limited voltage withstand capability. The Russian design employed a single-anode

mercury-arc valve (see Figure 3) and, for higher voltage, two such valves were used in series. The Swedish design used multi-anode mercury-arc valves with all anodes mounted on the common cathode tank (see Figure 2). When voltage higher than 125 kV was required, two complete six-pulse bridges were placed in series. The Swedish design used water cooling whereas the Russian design used oil cooling for the cathode. In 1961, English Electric Company UK signed an agreement with ASEA for the design and manufacture of mercury-arc valves and subsequently carried out refinements in the vacuum envelope. This resulted in the British development of the Kingsnorth valve and later the Nelson River I valve, which turned out to be the most powerful and the last mercury-arc

table 1. HVdc transmission schemes (1954–1976).

HVdc System	Commissioned	Rated Power (MW)	Rated Voltage (kV)	Rated Current (A)	Six-Pulse Bridge Voltage (kV)	Anodes/Valve	Transmission Distance (km)			Valve Type	Average Utilization Factor % (1967–1976)*
							Line	Cable	Total		
Gotland (Sweden)	July 1954	20	100	200	50	2	0	96	96	Merc	74.1
Cross Channel (United Kingdom, France)	December 1961	160	±100	800	100	4	0	65	65	Merc	24.2
Volgograd-Donbass (USSR)	October 1962–May 1965	720	±400	900	100**	1	472	0	472	Merc	18.4
Benmore–Haywards (New Zealand)	April 1965	600	±250	1,200	125	4	570	39	609	Merc	51.7
Konti-Skan (Denmark, Sweden)	September 1965	250	±250	1,000	125	4	95	85	180	Merc	39.0
Sakuma (Japan)	October 1965	300	2 x 125	1,200	125	4			0	Merc	4.8
Sardinia (Italy)	June 1967	200	200	1,000	100	4	292	121	413	Merc	21.2
Vancouver, Pole 1 (Canada)	July 1968–October 1969	312	±260	1,200	130	4	41	32	73	Merc	65.6
Pacific Intertie (United States)	May 1970	1,440	±400	1,800	133	6	1,354	0	1,354	Merc	48.3
Nelson River Bipole 1 (Canada)	June 1972–1976	1,620	±450	1,800	150	6	890	0	890	Merc	53.9
Eel River (Canada)	July 1972	320	2 x 80	2,000	40	NA			0	Thy	95.3
Kingsnorth (United Kingdom)	1975	640	±266	1,200	133	4	0	82	82	Merc	20.2
Cabora-Bassa (Mozambique, South Africa)	May 1975	960	±266	1,800	133	NA	1,420	0	1,420	Thy	—

*G.S.H. Jarret and R.M. Middleton, "A ten year review of HVDC transmission systems 1967–1976," *CIGRÉ Electra*, no. 57, pp. 35–46, Mar. 1978.

**Two single-anode, mercury-arc valves in series.

Merc: mercury arc; Thy: thyristor

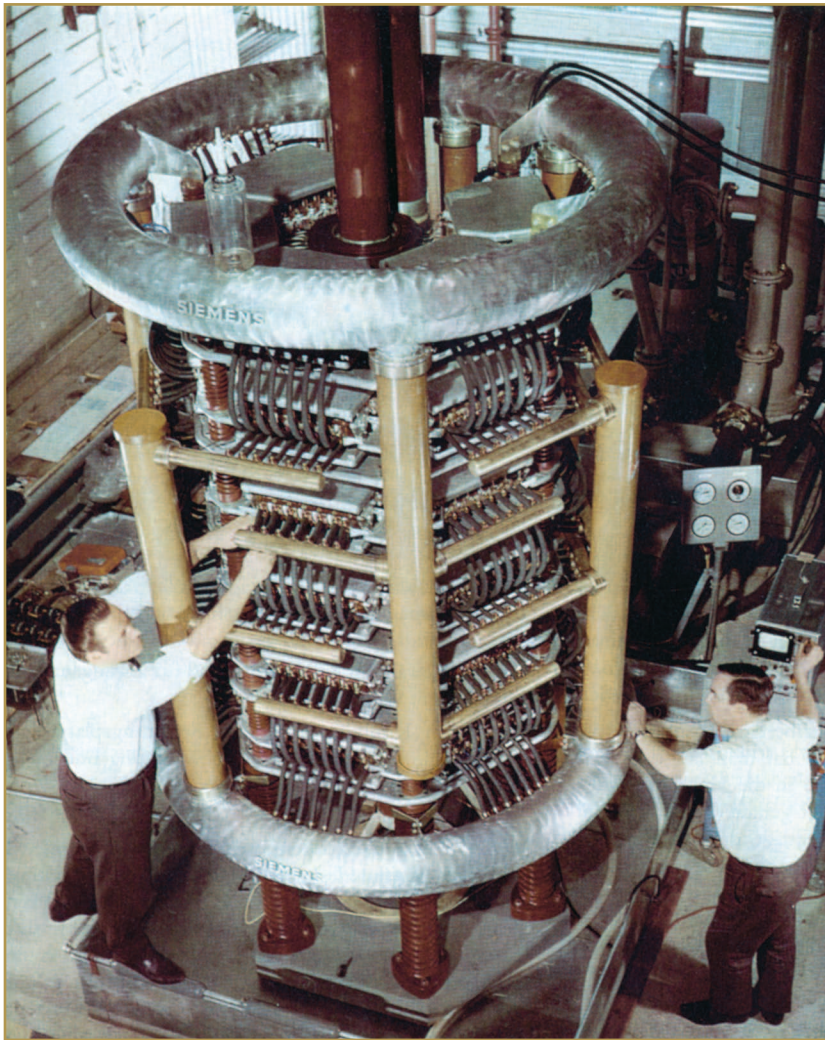


figure 5. A 100-kV, 1,000-A Siemens prototype thyristor valve (photo courtesy of Siemens AG, Siemens Corporate Archives, Munich, Germany).

valve dc transmission installation (see Figure 4). For the pioneering efforts of Dr. Uno Lamm of ASEA in Sweden, the Institution of Electrical Engineers (IEE) in Great Britain honored him with the title “father of HVdc power transmission” in 1965. In those days, his HV mercury-arc valve was exclusively being used in HVdc projects. The last mercury-arc valve developed by ASEA was for a current of 1,000 A/anode that never went into production because of the fast progress in the development of thyristor valves.

Because of the high conversion costs up to the mid 1960s, HVdc was favored only in conditions where ac systems encountered operational difficulties like sea crossings. Volgograd-Donbass

(USSR) was the first experimental and commercial extra-high-voltage dc (EHVdc) (± 400 kV) overhead transmission system commissioned in stages (initially at 100 kV, then at 200 kV, and finally at ± 400 kV) from 1962 to 1965; its utilization has been reported to be low (see Table 1). The first long-distance EHVdc (± 400 kV) line in the west (Pacific Intertie, United States) was energized in 1970 after a gap of 16 years during which the mercury-arc bridge capacity had increased 24 times. This system was followed by other long-distance dc links using mercury-arc valves.

Mercury-arc valves almost reached the peak of their development by the late 1960s when it was not possible to

further increase the blocking voltage of a mercury-arc valve. The voltage and power rating of dc systems were basically decided by two types of valve design available: 1) a four-anode valve with a six-pulse bridge rating of 133 kV, 1,200 A, 160 MW and 2) a six-anode valve with a six-pulse bridge rating of 150 kV, 1,800 A, 270 MW (see Table 1). The mercury-arc valve technology restricted the freedom of rating selections for converter valves to take maximum advantage of HVdc. Furthermore, the arc-back phenomenon necessitated the need for rapid switch-in and switch-out of relatively small power blocks. The major problems associated with mercury-arc valves that affected the performance of the converter station were

- ✓ arc-backs
- ✓ radio interference
- ✓ warm-up time
- ✓ a limitation in the rate of change of load
- ✓ less flexibility in voltage rating
- ✓ the need for degassing facilities
- ✓ higher maintenance
- ✓ larger valve halls
- ✓ the need for bypass valves
- ✓ deterioration in service.

There were also environmental issues associated with the operation of mercury-arc valves. Each sealed mercury-arc valve contained 2.64 qt (2.5 l) of mercury. During operation and maintenance of the valves, several pounds of mercury vapors were released to the atmosphere each year; hence careful monitoring around valve halls was required to manage mercury exposure. The mercury-arc-valve-based dc transmission systems were limited to the early 1970s (see Table 1). As of today, mercury-arc valves in all HVdc systems have been replaced by thyristor valves, except for one link.

Thyristor Valve Development

Selenium cells having rectification properties were discovered in the year 1883, but these became commercially available in the late 1930s only after the introduction of copper-oxide rectifiers. The drawbacks of metallic

rectifiers were a low operating temperature, current density, and voltage withstand per cell, resulting in bulky rectifier stacks and huge losses. The invention of monocrystalline semiconductors in the late 1940s changed the history of rectifiers. The semiconductor diodes (silicon and germanium) were compact because they could carry currents 1,000 times higher than metallic rectifiers. Silicon diodes had much better temperature withstand characteristics (175 °C) compared to germanium (65 °C). The problems associated with the preparation of good quality silicon crystals delayed its exploitation. Monocrystalline semiconductors offered advantages but required attention for heat dissipation and protection for fast changes of currents and voltages.

The next major step was the advent of silicon-controlled devices, a four-layer P-N-P-N semiconductor structure

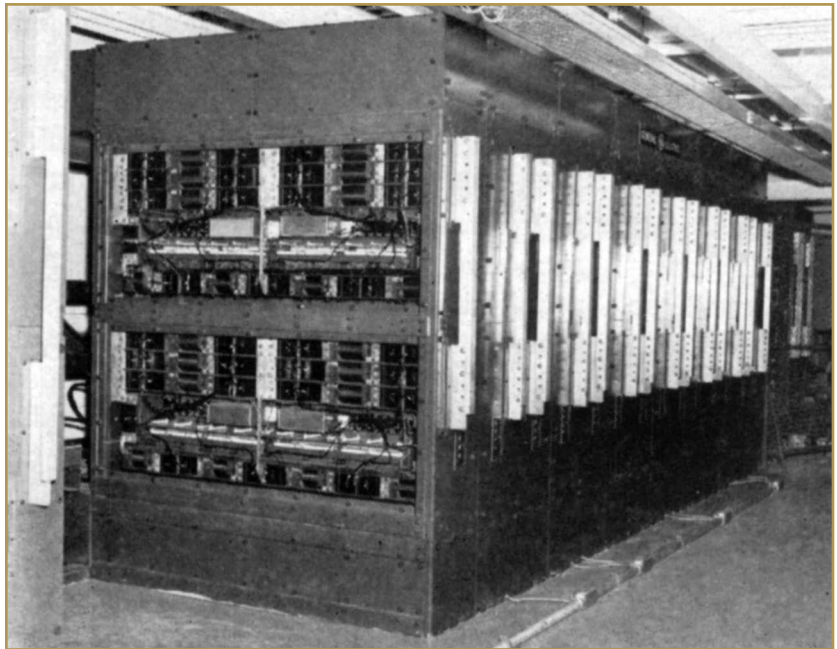
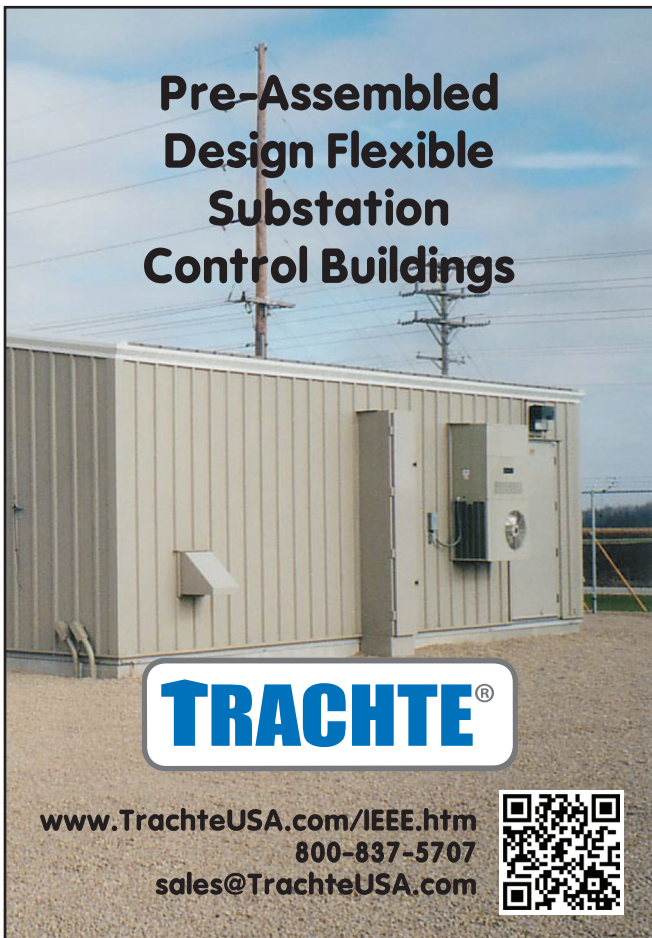



figure 6. A GEC thyristor valve converter for 20 kV, 36 MW (photo courtesy of the IEEE).

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with truly bistable characteristics. Its properties were superior to those of power transistors in many respects. Control could be performed by means of a low-power, short-duration pulse. The first silicon-controlled rectifier (SCR) was produced in 1957 by GEC in the United States. It worked at 300 V, 7A and required 15 mW for control. SCR was referred to by many names; the present-day name thyristor is an acronym of *Thyr*-atron and *trans-istor*, which was adopted in 1962. This device had the important characteristics of a) a high-resistance, HV blocking state in forward and reverse states, b) a low-resistance, low-voltage conduction state, c) the ability to remain in conduction after the application of a trigger pulse until the current dropped below holding level, and d) it conducted in both directions when it failed.

The thyristor brought together conversion and control into one device that led to significant savings in space and weight, as well as improvement in efficiency. Similar to the mercury-arc valve, the thyristor could not be turned off by a control pulse. However, it had a low forward voltage drop that made it suitable for low-voltage rectifiers, and it started replacing mercury-arc rectifiers in 1962. As thyristors started supplanting the mercury-arc converters, manufacturers all over world faced the most embarrassing situation, having invested large sums in developing sophisticated grid-controlled mercury-arc converters.

There was a question if thyristors could replace mercury-arc valves for HVdc. The technological gap between low-voltage industrial applications (a few kilovolts) and HVdc applications (hundreds of kilovolts) of thyristors was wide. To make a six-pulse bridge of 150-kV, 1,800-A rating, the standard rating of a mercury-arc bridge at that time, a large matrix of series-parallel thyristors with closely matched parameters was

required, where each thyristor had to be gated, cooled, and protected. There were problems associated with the firing of series-connected thyristors and voltage sharing during steady-state and transient conditions. Losses associated with the thyristor valve were 50–100% higher than those of mercury-arc valves. To reduce the valve losses and cost, it was essential to reduce the number of thyristors in a valve.

The advances in the thyristor manufacturing process improved thyristor characteristics and allowed rapid growth in device rating in the 1960s. By the late 1960s, thyristors with a blocking capability of 1.6 kV and a current rating of 900 A, equivalent to the current of a three-anode mercury-arc valve, were developed. It made solid-state technology an economical proposition for HVdc applications up to a voltage of 50 kV per valve,

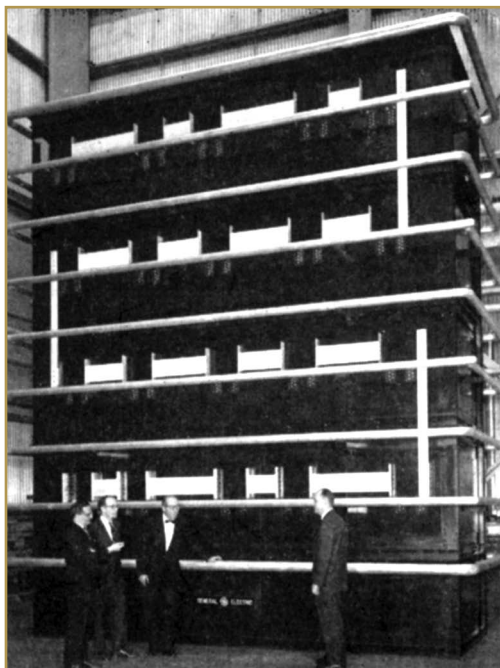


figure 7. One prototype thyristor valve for a GEC 220-kV, 360-MW, three-phase bridge converter (from *Proc. American Power Conference*, 1967, vol. 29, p. 995).

above which thyristors were still inferior to mercury-arc valves because of higher losses.

Different manufacturers all over the world started developing HV thyristor valves, and there were more than three large prototype valves on test in different countries. In 1963, an HVdc transmission (HVDCT) working group composed of AEG, BBC, and Siemens was formed to look at the possibility of the series connection of smaller mercury-arc valves, which concluded that future HVdc converters should be based on thyristor technology. The series connection of smaller mercury-arc valves was also being explored in the mid-1960s in Great Britain; there were serious drawbacks due to the multiplication of voltage drops and the additional requirement of grading circuits. Consequently, two members of

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figure 8. An ASEA thyristor test valve (photo courtesy of the IEEE).

the HVDCT working group, Siemens and BBC, constructed separately two powerful prototype thyristor valves for a rating of 100 kV, 1,000 A and 100 kV, 800 A, respectively, in 1967. These valves were tested together in a synthetic test setup at Mannheim–Rheinau (Germany) for a higher bridge rating of 120 kV, 900 A. The BBC valve was air cooled and made of 192 series-connected levels, and each level had two thyristors in parallel. The Siemens valve was a trendsetter in the sense that it employed forced oil cooling and

modular construction. It consisted of 180 series-connected disc-type thyristors (see Figure 5).

The prototype testing was such a success that in 1969 the consortium of Siemens, BBC, and AEG received the contract for the first thyristor valve-based long-distance HVdc transmission project (Cabora–Bassa). In test facilities, it was only possible to analyze how the valve would behave relative to impressed stresses. However, the real confirmation could satisfactorily be obtained in installations where other system components were represented. In 1967, GEC (United States) successfully tested 20-kV, 36-MW prototype thyristor converters in a back-to-back arrangement, thereby demonstrating the feasibility of the thyristor valve (see Figure 6). Subsequently, GEC manufactured one prototype valve for 200 kV, 360 MW for three-phase bridge converters (see Figure 7) in 1967 that paved the way for

commissioning the first thyristor valve-based HVdc project.

The testing of experimental thyristor valves in a running HVdc project was first conducted by ASEA in Sweden in 1967. It replaced one of the existing mercury-arc valves (50 kV, 220 A) in the Ygne inverter station of the Gotland link (see Figure 8). Two parallel assemblies of 56 thyristors were used for the valve, with each thyristor being rated for 2.8 kV. It operated approximately for two years without any disturbance until it was dismantled in February 1969. The operating experience gained was utilized to increase the rating of the Gotland link from 20 to 30 MW by the addition of a solid-state bridge in 1970.

All major requirements of power rectification from the late 1920s to the 1950s were met by mercury-arc rectifiers.

The common requirements for different valve designs developed by various manufacturers all over the world were

- ✓ a series, parallel connection of thyristors
- ✓ a current divider circuit

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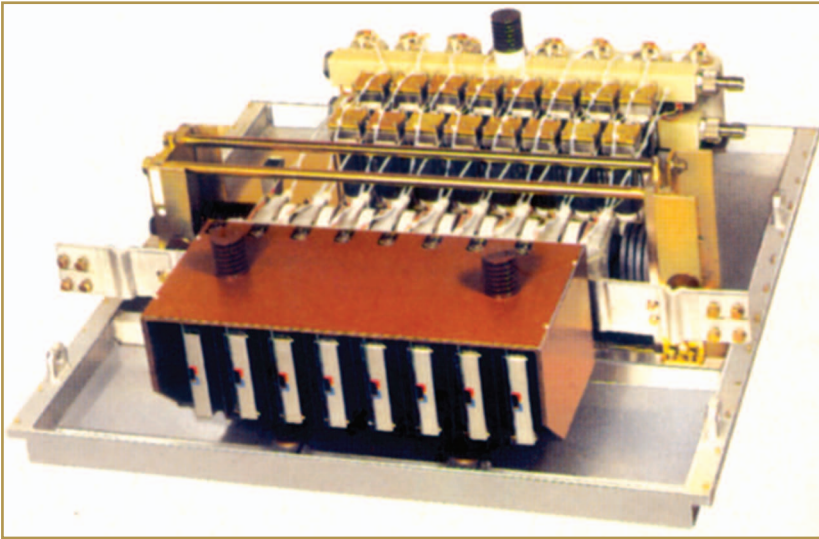


figure 9. A thyristor valve module, Acaray HVdc station, Paraguay (photo courtesy of Siemens AG, Siemens Corporate Archives, Munich, Germany).

- ✓ a resistive and combination of a capacitive, resistive voltage divider
- ✓ a saturable series reactor for high inrush current protection
- ✓ overvoltage protection
- ✓ a control pulse unit
- ✓ a signal transmission unit for firing pulse
- ✓ auxiliary power for gate drive
- ✓ a cooling circuit.

After nearly a decade of development, the first solid-state, valve-based HVdc project, Eel River (320 MW) in Canada, was commissioned in 1972 by GEC. Before this, nine HVdc projects based on mercury-arc valve technology were commissioned worldwide, and their availability was reported to be 83% in 1971. With the incorporation of solid-state valve technology, the plant availability increased drastically to as high as 98%. It was the confirmation of the successful development of the solid-state valve, and there was only one new installation of the mercury-arc valve after Eel River (see Table 1). Since then, dc transmission systems have been steadily growing because of the thyristor's simple design, predictable performance, reduced maintenance, and need for less area. The space required for mercury-arc converters was about 3.5 m²/MW compared to 1 m²/MW for thyristor valve converters of similar rating. The valve hall for the Volgograd-Donbass inverter was 722 ft (220 m) long. The major advantage of the thyristor valve is that it is made up of series of incremental valves. If properly designed, any fractional valve failures do not impair the performance of the valve. This permitted a great flexibility in deciding bridge rating and thus allowed optimization of HVdc links from the point of view of line and system.



figure 10. An outdoor dead tank thyristor valve, Cabora-Bassa HVdc link; from BBC brochure CH-A-023 880 E (photo courtesy of ABB Asea Brown Boveri Ltd., Zürich, Switzerland).

Many new design innovations improved the power-handling capacity of thyristors. The press-pack/flat-pack/hockey-puck thyristor design allowed two sides for cooling, which almost doubled the device's capability. A more important advantage of the flat package was its ease in adopting a stacked array modular valve (see Figure 9). The capability of thyristors was limited by using forced-air cooling that was also very noisy. By utilizing oil as a coolant and insulating medium, it improved valve cooling and resulted in a compact design for the first outdoor dead tank valve for the Cabora (now Cahora)-Bassa link between Mozambique and South Africa in 1975 (see Figure 10). The hazardous nature of oil and the increase in stray capacitances discontinued its future use. The technology developed for the water cooling of the mercury-arc valve was helpful in its application to the thyristor valve. This improved the cooling efficiency several fold and the device capability. It was first used in the Nelson River II project in Canada in 1978.

HVdc converter size is dictated by the thousands of thyristors used in the converter valves, and it directly affects economics. Eel River has 200 (4 × 50) thyristors for each valve for a rating of 40 kV, 2,000 A. Hence, it was necessary to improve the switching power of thyristors. The lateral resistivity variations across silicon wafers would not allow the utilization of its full potential. The major breakthrough was the discovery of the neutron irradiation doping process that made silicon extremely homogeneous. It paved the way for the production of thyristors with high blocking voltages and currents. This technology was first commercially utilized for HVdc transmission in 1978. With the availability of silicon wafer sizes of 4.92-in (125-mm) diameter and larger, a current of 4,000 A could be easily handled.

Spreading gate current into fingers over the wafer area enabled the rapid control of several thousand amperes. An interesting example is the involute and interdigitated gate geometry used

for thyristors. HVdc thyristor valve technology has come a long way; the Eel River valve would need fewer than 20 thyristors in place of the 200 used in 1972. Thyristors with voltage ratings as high as 9 kV are in operation, and thyristors with 12-kV blocking capability have been developed. The power-handling capability of the thyristor converter bridge (six-pulse) has seen a phenomenal rise; it has reached as high as 750 MW from a mere 80 MW in 1972, which is approximately three times more than what a mercury-arc valve bridge could handle previously (see Table 1).

Conclusion

The valve, which blocks and conducts current periodically, is truly the heart of HVdc. There were complex factors associated with mercury-arc valves that didn't permit the precise prediction of its performance, whereas the performance of thyristor valves can be predicted with remarkable accuracy. The advances in the solid-state valve have made HVdc economically much more competitive. As a consequence, more and more HVdc links have been commissioned, and many more are being planned throughout the world. There is an unending requirement for improving the thyristor valve. It calls for larger capacity thyristors, lower losses, lower maintenance, and higher

reliability. The use of power electronics in power systems is increasing significantly with thyristor capability. In the future, ac-dc combinations will make the most efficient use of renewable energy without affecting the environment. Silicon is the best medium for the conditioning of electrical power into usable form. It is extraordinarily stable and has long life when processed and used properly.

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