HVDC Transmission: Yesterday and Today

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A Brief Look at the History of HVDC to Help Understand Its Bright Future

IT GOES BACK TO THOMAS ALVA EDISON, OF COURSE. IN 1876 HE ESTABLISHED HIS research laboratory at Menlo Park, New Jersey. A commercial dynamo (dc generator) appeared in 1879, an incandescent lamp the same year, and in 1882 the Pearl Street Station began providing electrical energy to New York's financial district (via 100,000 feet of underground cables!). The energy source was a cluster of six "jumbo dynamos" of 100 kW, each capable of lighting 1,200 light bulbs. The electric era had begun, using direct current.

Soon after there followed the Edison-Westinghouse "debate" on the relative safety of dc versus ac. The focal point was New York State's interest in a more "humane" means of execution of criminals. Edison, the proponent of dc utilization, endorsed Westinghouse's ac for the task implying that dc was safer for humans. The two did not debate, per se, but in fact ac was selected and William Kemmler was electrocuted in 1890. (An interesting sidebar to this tale is that Edison was opposed to capital punishment.)

The dominance of dc was brief, and George Westinghouse joined with Nikola Tesla and others to capitalize on the performance advantages of transformers and induction motors. Alternating current generation, transmission, and utilization were, and remain, dominant. (Additional details on the controversy between ac and dc are found in the 2006 book *AC/DC: The Savage Tale of the First Standards War.*)

A second sidebar: In 1884 Edison was named one of six vice presidents of the American Institute of Electrical Engineers (AIEE), a forerunner of the IEEE. One wonders who the president and other five vice presidents were! The interested reader is invited to visit ieee-virtual-museum.org for additional historical information.

But, returning to our principal topic, the next section of this article portrays some of the early developments in modern high-voltage direct current (HVDC) transmission. Today there are 16 dc links operating or under construction in the United States and 21 in North America (Figure 1). There are additionally numerous links throughout Scandinavia as well as in Japan, Australia, Brazil, South Africa, India, China, and others; well over 100 world wide. And, many others are planned, especially in India and China (Figure 2). HVDC transmission is an important contributor to successful power system operation. The history is interesting; after a period of comparative dormancy the future is unexpectedly bright.

Dr. Uno Lamm, Earliest Projects, and Players

Direct current is by many considered to be the preferred means for distribution of electric power. However, the ease of transforming ac from one voltage level to another has made ac the technology of choice for transmission and distribution of electric power even though the ultimate use of electric power is often a dc source, for instance the power used for driving our electronic

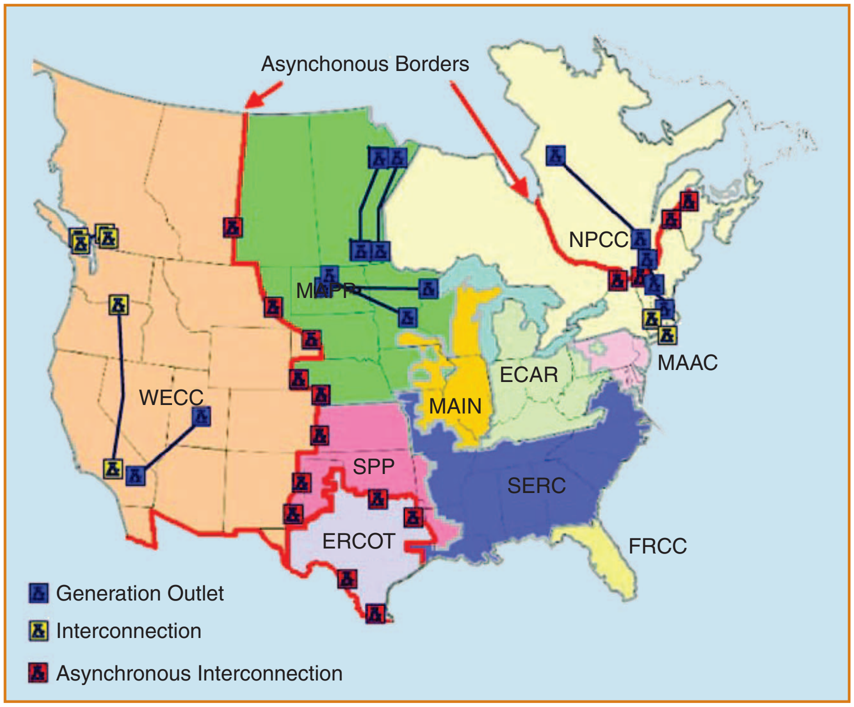

figure 1. HVDC systems in North America.

processing chips. Most of the early attempts for transforming dc voltage to higher or lower voltage levels relied on mechanical means, which are not practical. Therefore, other methods using plasma devices were sought by those interested in conversion technologies. However, construction of the needed switching equipment was difficult because the devices could not withstand high voltages because the voltage withstand of a gap between an anode and a cathode inside a switching device is not proportional to the gap's dimensions. Some, like E. Marx in Germany, worked on high-pressure arc rectifiers. Dr. Uno Lamm, who worked on low-pressure mercury arc converter valves for low-voltage applications, got the idea around 1929 to place grading electrodes in the gap of the valve and thereby increase the voltage withstand of the gap. This was effective and eventually Dr. Lamm and ASEA were awarded a patent on the invention. However, as is often the case with inventions, before a practical converter valve based on Dr. Lamm's design could be built, numerous technical problems had to be overcome. Many of these were associated with materials and manufacturing issues. Thus, another 10–15 years would pass before the invention could be incorporated into a manufacturable converter valve. For his efforts, however, Dr. Lamm had an award named for him (see "The Uno Lamm HVDC Award").

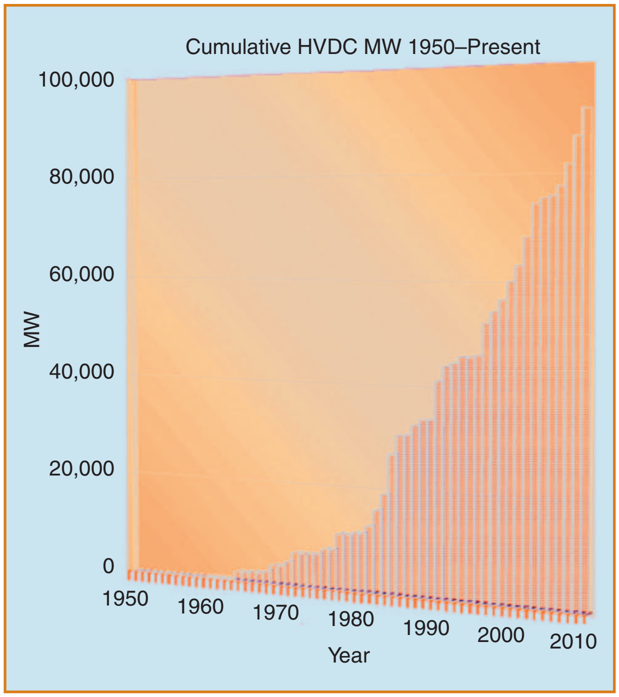

figure 2. HVDC systems worldwide: Cumulative megawatts versus year of commissioning.

The 1930s: Early Research Efforts

The 1930s were a very active time period for research on HVDC converter technology. Development of HVDC technology was not limited to Sweden. In fact, the literature is dominated by papers and articles by German authors although researchers and engineers from Russia, Switzerland, France, and the United States can also be found among those publishing significant papers related to conversion of ac to dc and vice versa ("An annotated bibliography of high voltage direct current transmission 1932–1962," presented before AIEE Winter General Meeting, New York, 1963). The topics presented in the published papers cover among other things:

- ✔ development of theory related to static converters for ac to dc and dc to ac conversion
- ✔ economics of dc transmission systems including the distance at which dc would be cheaper than ac
- ✔ converter system topologies
- ✔ developments of converter valves, without which there can be no feasible HVDC converters
- ✔ Corona, insulator, and transient performance of overhead dc lines
- ✔ insulation systems in equipment.

There were even some papers on feasibility or technology demonstration systems that were built, including:

As is often the case with inventions, before a practical converter valve based on Dr. Lamm's design could be built, numerous technical problems had to be overcome.

- ✔ a 20-MW, 125-kV, 275-mile line between Moutiers and Lyon, France (1936)
- ✔ a 0.5 MW, 50-kV line from Wettingen to Zürich, part of the Swiss Exhibition in 1939
- ✔ a 33-kV, 400-A BBC test plant in Biaschine, Germany (1946).

Additionally, there are reports of a test system in Berlin, Germany, which was dismantled and brought to Russia after World War II.

The 1940s: HVDC Still Not Quite There

After the end of World War II the need for electric power was great. Exploitation of hydro power, where this was feasible, usually required long transmission lines since the water resources are typically in mountainous regions whereas the population centers are usually distant. In Sweden, the hydro resources are located in the northern regions of the country and the population centers are in the southern part. Sweden is not unique in this regard, but the distances between generating plants and the load centers are possibly longer than in many other countries. At least, in the late 1940s, there were not many other countries facing similar problems. The engineers at the Swedish State Power Board took a good look at HVDC before deciding that the converter technologies were not yet at a point where dc could be considered, and therefore 380-kV series-compensated ac lines were developed instead. However, the interest in HVDC remained. The focus was now on the following topics:

- ✔ all aspects of dc transmission systems via overhead lines and cables
- ✔ earth return studies
- ✔ laboratories for testing
- ✔ continued feasibility demonstrations.

In 1945, the Swedish State Power Board (later renamed Vattenfall) and ASEA constructed a 50-km test line between Trollhättan and Mellerud in Sweden and a valve testing facility in Trollhättan. This test line provided substantial experience for ASEA's development of converter technology, in particular for validation of different converter valve designs.

The Uno Lamm HVDC Award

In 1980 the IEEE Power Engineering Society conceived the idea to offer an annual award to an eminent engineer or scientist working in the area of HVDC transmission. The Swedish company ASEA was approached for financial support, as the intent was to name the award after Dr. Uno Lamm. This was agreed to by Gunnar Engström, vice president of transmission and distribution, with several caveats. First, ASEA could nominate but not direct who the awardee should be; second, it was strongly suggested that the initial awardee not be from that company. A group of eight HVDC experts was formed to comprise the committee. Financial support from other suppliers and utilities was added to the initial amount. The first award was made at the 1981 Summer Power Meeting and, surprise, it went to ASEA's Dr. Erich Uhlmann for his pioneering work in main circuit design and overall system analysis. Subsequent awards have gone to John Ainsworth of GEC, Narain Hingorani of EPRI, Karl-Werner Kanngeisser of BBC—to date a total of 21 persons from nine countries. The list of awardees is a veritable who's who (or perhaps who was who) of HVDC technology.

Dr. Uno Lamm (right) with Gunnar Engström, circa 1985.

The 1950s: Major Steps

The developments of HVDC technologies accelerated in the 1950s probably because the technology seemed to be close to commercially feasible. The literature covers the same topics as had been written about in the 1930s but more in depth. New topics included the use of physical simulators for the design of dc systems, modeling of equipment, and radio interference from converters.

It was also realized that the costs of HVDC systems would be quite a lot higher than for ac systems excepting if cables were needed for the transmission link. This was and still is the case where undersea cables are needed because of length-dependent reactive power consumption of ac cables. Another application would be where ac systems are so little developed that stable operation is difficult to maintain with ac lines. This was the case in Russia where the vastness and the sparseness of population centers makes it difficult to economically build a strong, integrated ac transmission system. A feasible option was HVDC transmission for high-power long-distance overhead lines.

It was probably fortunate for ASEA that a near-term application for HVDC in Sweden was to supply the island of Gotland in the Baltic with cheap hydropower from the Swedish mainland. This would require a moderately rated system. From the late 1940s until the mid-1960s, the history of HVDC outside Russia is really the history of ASEA since there was no other viable supplier of HVDC valves.

Interest in HVDC technology was so great that a special magazine called *Direct Current* was launched in England beginning in June 1952. The founder and first editor was J.H.M. Sykes, and it was published in England by Garraway, Ltd. While HVDC transmission was the principal interest, the magazine also addressed traction, low-voltage dc generation and application, and research and development. The magazine continued for about 15 years, published quarterly except sometimes monthly, until the untimely death of Sykes. In April 1969, *Direct Current* reappeared for several years under the joint editorship of Colin Adamson and Jos Arrilaga of Manchester University, published by Pergamon Press, England.

The first commercial order for an HVDC system was given to ASEA by Vattenfall for a 20-MW, 100-kV undersea cable between the Swedish mainland and the island of Gotland in 1950. The converter stations, one of which is shown in Figure 3, were built using two series-connected 50-kV six-pulse converter groups operating as a 12-pulse converter.

Each valve had two parallel–connected anodes each rated 100 A producing the needed 200-A dc output. Dr. Erich Uhlmann, who had joined ASEA in the 1930s, was responsible for the system design, and Harry Forsell contributed to the control system design. The island of Gotland had almost no local generation, and a requirement of the dc link was that it should be able to supply the island with power in the absence of any local generation. This is a requirement that until today no other dc system has been required to meet. The solution was to install a 30-MVA synchronous condenser at the inverter station on Gotland. After the condenser was rolling at a frequency of a few Hz, the converter was started, the condenser brought up to synchronous speed, the ac breaker was closed, and the load was picked up. Control of the ac system frequency at the inverter terminal was used during such “islanded” operation. To accomplish this, two redundant radio links were used across the approximately 90-km distance between the rectifier and the inverter ends. The two radio links were operated at different frequencies to as much as possible avoid simultaneous fading of both links. Power reversal was also possible to use in the rare case that excess capacity was to become available on the island. The converter station on the Swedish mainline was remotely controlled from the island. Thus, the Gotland HVDC link was in many respects more advanced than other dc schemes in the world today. The Gotland HVDC link was commissioned in March of 1954. In 1955 Gunnar Engström succeeded Uno Lamm as the manager for ASEA’s dc transmission department.

As is often the case, new technology typically requires a champion, which in this case was Vattenfall, and a successful demonstration before others (the “early adopters”) are willing to risk using the new technology. The literature in the late 1950s is rich with feasibility or conceptual dc system studies for transmission of power; for instance, between England and France, between the North and South islands of New Zealand, Norway to Denmark, in Canada, and in the United States. The next commercial system order was awarded to ASEA in 1957 for a 160-MW link at ±100 kV between England and France. This was the Cross Channel project that was commissioned in 1961. The main technical lesson from this project was that harmonic instability can be caused by dc saturation of the converter transformers caused by unbalance in the valve firing systems if the positive and negative current half cycles are not perfectly balanced. Harmonics in the transformer magnetization currents can then interfere with the valve firing system leading to positive feedback if the connected ac system has unfavorable characteristics for the specific harmonic frequency. These problems were analyzed and solved by Erik Persson, ASEA’s control systems expert. The recognition of the potential for harmonic instabilities led to developments of new control system concepts, so this is no longer an issue.

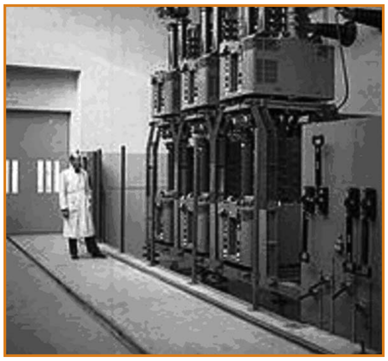
figure 3. A six-pulse converter valve group for the Gotland link with Uno Lamm observing.

The 1960s: Spreading the Technology

Early in the 1960s, ASEA received three orders for HVDC transmission schemes. The first of these was the Cook Straits

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600-MW, ±250-kV project from the Benmore hydropower station on New Zealand's south island to the north side of the strait. This system made use of both a long overhead line and an undersea cable through the Cook strait. The second was a 250-MW, 275-kV link between Sweden and Denmark, and the third was for the Sakuma project in Japan. This was a 300-MW, 2 × 125-kV, back-to-back, 50/60-Hz frequency converter, which was a new application. These systems were all commissioned in 1965. ASEA's management realized, however, that it could not continue as a sole source supplier of HVDC technology and therefore executed license agreements with English Electric in the United Kingdom (now a part of Areva) and General Electric Company in the United States. As a consequence, the next commercial order for a dc project, the 200-MW, 200-kV undersea cable link between Sardinia and the Italian mainland, was awarded to English Electric. This was commissioned in 1967.

The 1970s: Computers Take Control

The next major technology advance was associated with the 1,440-MW Pacific HVDC Intertie between the Columbia River in Oregon and Los Angeles, California The present-day Celilo converter station at the north end of the link is seen in Figure 4. This was an ASEA-General Electric joint venture for an 856-mile long bipolar overhead line operating at ± 400 kV. It was the first HVDC line designed to be imbedded in an ac network. Three 133-kV six-pulse converter groups were used in each pole. The 1,800-A converter valves for these stations had six anodes each rated 300 A but designed to handle 360 A for one hour. The most remarkable aspect of this system was that it was originally conceived as a multiterminal system with one line from The Dalles, Oregon, to Los Angeles, and a second line from The Dalles to Lake Mead close to Las Vegas, Nevada. The system was to be built using a common line segment from Oregon to a location in Nevada in case there was a problem with one of the two parallel lines on this segment of the system. A line between Lake Mead and Los Angeles was discussed as a possibility, potentially making this a four-terminal system with two terminals in parallel at The Dalles, one at Lake Mead, and one in Los Angeles. The line between The Dalles and Lake Mead was cancelled soon after President Richard Nixon took office but the idea to connect the Columbia River electrical generation system with Lake Mead is still alive.

One of the technical problems that had to be solved was how to protect dc systems from overvoltages. Prior to the Pacific Intertie, no adequate surge arrester was available to protect the dc converter stations from overvoltages originating from the dc side of the system. AC arresters could not interrupt the surge currents and would therefore fail if they were triggered. This led to adaptation of new arrester technologies for dc applications by a team from General Electric. Another first was the use of digital process control computers for control of the dc system. This was probably the world's first transmission system controlled by means of a distributed computer system configured as a multiprocessor, multitasking real-time control system. This was a major advance because it demonstrated that process control computers could survive in the harsh electrical environment of a high-voltage substation. One computer was placed in each converter station communicating 856 miles over a microwave link. Operator consoles were located at each station and in the Bonneville Power Authority (BPA) dispatch center in Vancouver, Washington, as well as in the operations center for the Department of Water and Power in downtown Los Angeles. Start, stop, and load levels were implemented in software and automated, relieving the operators from making many complex decisions. Some protective functions such as overload protection and dc line protection coordination functions were also implemented in the software. This became the model for later developments for microprocessor-based digital systems for control, monitoring, and protection of ac systems. This is an example of the unconventional technologies developed for HVDC that later found applications in ac systems. (Additional information on the Pacific HVDC Intertie is found in the companion article by Wayne Litzenberger and Peter Lips on page 45 of this issue.)

There were significant concerns about the performance of the converter valves at the time when this system was procured because the operational experience from the ASEA systems commissioned in 1965 had a much higher arc-back frequency than expected (reverse voltage breakdown when in rectifier

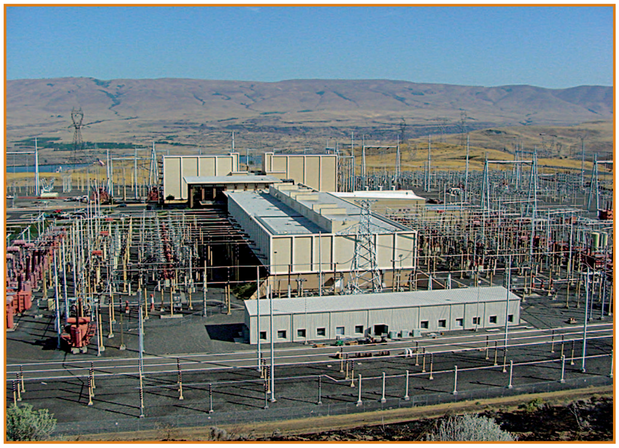

figure 4. Present-day Celilo converter station.

The technology is now at a point where ±800-kV dc links for long-distance power transmission systems rated up to 10 GW are on the verge of being built.

operation). What was even worse, so-called consequential arc-backs, a multiple arc-back that cannot be cleared by means of grid control of the valves and requires operation of the ac breakers for the converter groups to clear, had arisen as a major reliability issue. This actually led to the end of mercury arc valves for HVDC. Following the Pacific HVDC Intertie, Nelson River and the Kingsnorth systems built by English Electric became the last systems using mercury arc valves. More about this below.

Major Projects and Advancements

Thyristor Converters

The solid–state thyristor took over from the mercury arc valves beginning in the late 1970s. There were several factors driving the technology toward solid-state converter valves. One was the opportunity for a German consortium to develop an alternative to mercury arc valves. ASEA had to withdraw from the Mozambique to South Africa Carhora-Bassa project after the project was awarded to the consortium in which ASEA had participated (if ASEA had delivered equipment to Mozambique it may have violated Swedish export laws). This 1,360-km long line was rated 1,920 MW, operating at ±533 kV bipolar, and commissioned in 1978. This left AEG, BBC, and Siemens, who were members of the winning consortium, with the challenge to develop alternative valve designs, and thyristor technology was the basis for this design. Furthermore, since there were only two suppliers (with ASEA being the leader of mercury arc valve technology), there was a lack of competition for dc projects, which probably limited user acceptance and most likely reduced the potential market for HVDC systems. The barriers to entry to others who might be interested in the mercury arc technology were formidable. Large investments were needed to establish laboratories and the know-how barrier was also very high. Thyristor technology offered a viable alternative to those not having access to mercury arc valves. The final blow to the mercury arc valve was, however, the propensity for arc backs and consequential arc-backs. In addition, mercury arc valves required frequent overhauls requiring special facilities at the converter stations plus a skilled crew of maintenance people to perform the overhaul. This imposed a significant cost penalty on the mercury arc valves.

figure 5. Gotland Converter Station with mercury arc and thyristor valves.

General Electric emerged in the late 1970 as a viable supplier of HVDC systems using thyristor valves. GE had significant know-how on how to make these semiconductors, which can be designed with predictable performance. The most remarkable aspect of this technology revolution was, however, that ASEA was able to abandon the mercury arc valves and, thanks to a thyristor technology license from GE, also emerge as a leader of the solid-state converter valve technology. Few companies are able to make such a technology transition with relative ease.

In 1970 ASEA was able to get a 10-MW thyristor-based converter group added to the 100-kV Gotland link, which increased the voltage on the cable to 150 kV. Thus, ASEA was the first to demonstrate they new valve technology (Figure 5). However, General Electric's 320-MW Eel River back-to-back system operating at 2 × 80 kV, commissioned in 1972, was the first all-solid-state converter system in operation. English Electric, BBC, Siemens, Hitachi, Toshiba, and Mitsubishi have followed suit and supplied converter systems based on solid-state converter valves. The thyristors have enabled the suppliers to optimize the HVDC offerings by tailoring the devices to each specific application and dc power level.

A number of 100- to 200-MW back-to-back systems have been built for connections across the continental divide, between Quebec and New England, and for connections between Texas and adjoining states (refer back to Figure 1 for these and other North American systems). All of these employ thyristor valve converters, as have the long-distance systems from the late 1970s onward (Square Butte, CU, Intermountain, etc.).

The next step forward in HVDC transmission involved multiterminal systems. The first of these was the addition of a 50-MW converter station on the island of Corsica for tapping the Sardinia to the Italian mainland HVDC submarine link. General Electric provided key technologies such as valves and controls

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for this tap. The system was commissioned in 1986 after General Electric had sold its HVDC business to CGEE Alsthom, France. The Nelson River system was also conceived as a multiterminal (parallel bipoles) system. English Electric/GEC of the United Kingdom supplied the initial converters for a 900-MW, ±463-kV system (1979); it was later expanded by the German consortium into a second bipole bringing the power in 1985 up to 2,000 MW at ±500 kV.

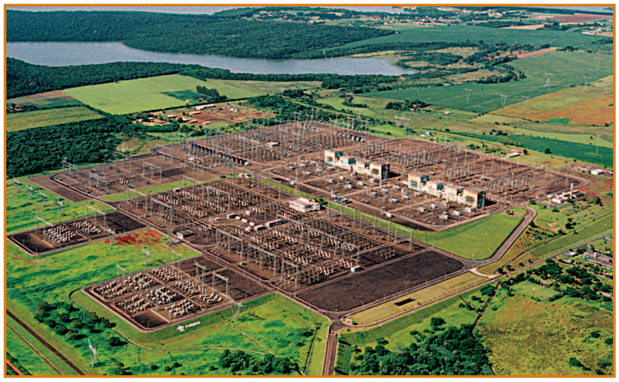

figure 6. The Itaipu Converter Station at Foz do Iguacu.

Toward 800-kV HVDC

The major technology leap was, however, in Brazil, with the 3,150 MW, ±600-kV Itaipu project commissioned in stages from 1984 through 1987. The overhead line is about 800-km long. Each 12-pulse converter is rated 790 MW, 300 kV. This link brings hydropower generated at 50 Hz from Foz do Iguacu to Sao Paulo in Brazil. The converter terminal at Foz do Iguacu is seen in Figure 6; it measures approximately 960 m by 800 m. (More information on this system is included in the article by Marcio Szechtman, et al., appearing in this issue of *IEEE Power & Energy Magazine* on page 61).

The Quebec-New England HVDC system comprises five terminals but operates principally to bring hydro power from James Bay in Canada to the Boston, Massachusetts, area. It is rated 1,500 MW, ±450 kV, and was completed in 1992. Additional details are found in the article on HVDC planning issue by Mike Henderson, et al., which can be found on page 52 of this issue of *IEEE Power & Energy Magazine*.

HVDC has found major applications in countries making heavy investments in their electric power systems and building a new transmission system to support primarily the development of remote hydropower resources. This is occurring both in India and in China, where a large number of high-power,

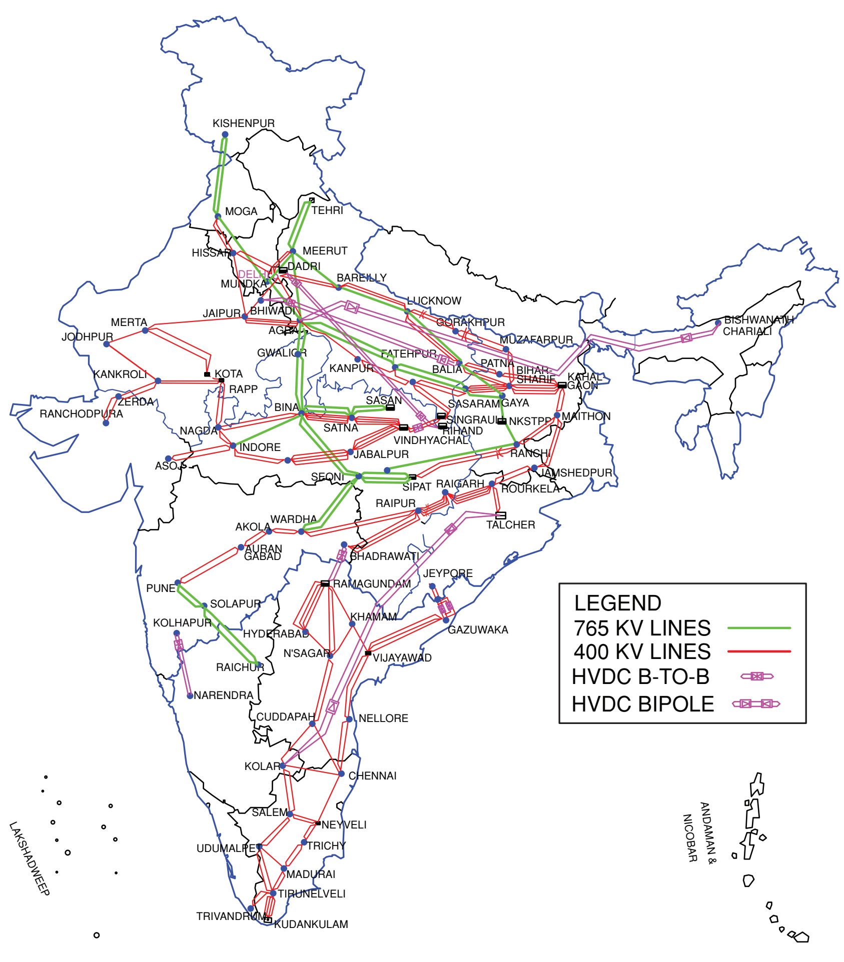

figure 7. Projected HVDC links in India by 2012.

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thyristor-valve-based HVDC systems have been built and more are planned. Figure 7 shows a map depicting what the transmission system might look like in India in the year 2012. This has also led to additional suppliers of HVDC converter equipment in India, and more are likely to emerge as a result of the high demand for HVDC equipment in those countries. The power levels and transmission distances are such that HVDC systems operating at ±800 kV might be needed. (Again, the reader is referred to the 800-kV article by Marcio Szechtman et al).

“HVDC Light”

At the other end of the HVDC system power spectrum, the insulated gate bipolar transistor (IGBT) developed for motor drive and similar applications has begun to find applications also in HVDC systems at the lower end of the power range and at moderate dc voltage levels. These systems operate using pulse width modulation (PWM) techniques, which enable savings in filters. There is little or no need for reactive power compensation since these converters can generate reactive as well as active power, which leads to a smaller footprint for the converter stations. (ABB has coined the term “HVDC Light” for these systems.) These systems have found applications for transfer of power from off-shore wind farms and short-distance XLP-type cable systems. The first commercial HVDC Light project was the 50-MW underground cable link from the southern part of the island of Gotland to the city of Visby at the northern end of the island. Thus, Gotland had again served as the proving ground for new ABB-developed HVDC technology. The largest system to date is the 330-MW Cross-Sound dc link between Connecticut and Long Island.

Putting the Pieces Together

Although this history to a large degree is the history of ASEA’s HVDC developments because ASEA was first to the market with major technology innovations, the modern HVDC transmission system technology would not have been possible without other developments. The thyristor, for instance, was proposed by William Shockley in 1950 but was first commercialized by General Electric in 1956. General Electric developed very powerful thyristors, which enabled the Eel River and other General Electric projects. Development of improved high-quality, large-diameter silicon material had to precede development of the large-diameter, high-voltage, sometimes direct-light-fired and self-protected thyristor devices used in the largest HVDC converter valves. These developments have been pursued all over the world involving many different companies. General Electric was the early technology leader but ASEA/ABB, Siemens, Toshiba, Mitsubishi, and others have also contributed to the advancement of the device technology. The oil-insulated outdoor thyristor valves for Carhora Bassa represented technology innovations developed by Siemens, AEG, and BBC. English Electric first utilized equidistant firing concepts that reduced the risk of harmonic instabilities in the firing of the converter valves. The insulation aspects of the oil-paper insulation systems in converter transformers and reactors had to be researched to enable the transformer designers to build transformers and reactors that could withstand the unique dc voltage stresses. The technology is now at a point where ±800-kV dc links for long-distance power transmission systems rated up to 10 GW are on the verge of being built.

Web Sites of Interest

The HVDC and FACTS Subcommittee of the IEEE/PES Transmission and Distribution Committee has a Web site currently located at www.ece.uidaho.edu/HVDCfacts. Of particular interest is a compilation of worldwide HVDC projects titled “HVDC Projects List.” This listing is managed by Robyn Taylor, subcommittee secretary; it is a living document being constantly updated, so caution is urged when referring to it. Soon to be added is an annotated bibliography of HVDC and FACTS publications (this compilation began at Bonneville Power Administration in 1963.)

A second Web site is that of the High Voltage Power Electronics Stations Subcommittee of the Substations Committee, currently found at www.tc.umn.edu/~chris143/.

A third Web site is that of CIGRE Study Committee B4, HVDC and Power Electronic Equipment. It is found at www.cigre-b4.org There one can find the minutes of recent meeting of the Study Committee with complete reports from working bodies of that study committee (click on “Cigre Events”). Also included are reports from current and planned projects around the world. Additionally, there are links to the home pages of HVDC equipment suppliers.

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The Selected Articles in This Issue

In 2001 the HVDC/FACTS Subcommittee of the PES Transmission and Distribution Committee formed a working group on HVDC/FACTS Education. (See "Web Sites of Interest.") The task assigned was to develop introductory panel sessions for selected PES meetings in order to familiarize persons with the characteristics of power-electronic-based transmission controllers. (There have been four such panels offered to date.) This was thought to be especially beneficial to younger engineers and could provide a doorway for their participation in PES activities. So the motivation was both educational and professional—a way to interest younger engineers in the work of the IEEE Power Engineering Society.

At the 2006 Power Systems Conference and Exposition, the working group presented the panel session "HVDC System Solutions" to 35 attendees. Brian Johnson, University of Idaho, organized and chaired the session. Quoting from the session summary,

"There has been a renewed interest in the application of High Voltage Direct Current (HVDC) transmission schemes in recent years. This session introduces fundamental concepts of HVDC transmission schemes, but not through a deluge of complicated circuits. The first presentation will discuss what HVDC schemes can and cannot do along with an overview of HVDC fundamentals. The second presentation will include an overview of some existing HVDC applications, centered on the Pacific HVDC Intertie, with discussion of the benefits of these projects. The final presenter will discuss application experiences in Eastern North America and discuss the implementation of HVDC schemes in planning studies."

As the planning for the session proceeded, the question was raised if these papers could form the basis for an issue of *IEEE Power & Energy Magazine* devoted to HVDC power transmission. This article and those that follow are the answer to that question. The three panel papers have been revised and augmented, and a fourth paper on ±800-kV HVDC transmission has been added. To date, the highest operating voltage is ±600 kV, but clearly ±800 kV lies ahead only a short distance.

We hope you find these articles informative and interesting. HVDC transmission is an important component in today's power systems.

Acknowledgments

Appreciation is expressed to Mike Bahrman, ABB, for several photographs in this article and others in this issue; to the Brazilian utility Furnas for the photograph of the Itaipu converter station; to Power Grid Corporation of India for the 2012 map; and to Robyn Taylor, Teshmont Consultants, for the HVDC Projects List adapted for Figure 2.

For Further Reading

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Biographies

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