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Uno Lamm

the father of HVdc transmission

IN THE EARLY 1920s, AUGUST UNO Lamm had a vision that would ultimately take decades to come to fruition and change the world forever. Lamm, who is widely referred to as the father of high-voltage (HV) dc transmission, invented the first economical way to convert ac to dc and then back again. His discovery and development of the HV mercury-arc ionic valve paved the way for efficient and practical HV transmission.

Comparable to visionaries Steve Jobs and Steve Wozniak, who presented the early Apple I board when they were in their early 20s, Lamm was 25 when he was granted a patent for the high-power mercury-arc ionic valve, not long after he graduated with a master's degree in electrical engineering from the Royal institute of Technology, Stockholm, Sweden, in 1927. And, like Jobs' and Wozniak's perseverance with Apple, Lamm did not let detractors or distractions keep him from inventing and nurturing the technology that one day would reach people worldwide.

As a young manager at the Swedish electrical equipment manufacturer Allmanna Svenska Electktriska Aktiebolaget (ASEA), Lamm knew that dc was the oldest and most dependable form of electrical generation and transmission. But at the time, published reports show that Lamm faced considerable obstacles and skeptics as he developed the mercury-arc valve. According to a 1981 article in *IEEE Power Engineering Review*, "Difficult materials problems had to be overcome and the first experiments had to be squeezed in between many other more pressing claims on the experimental and personnel resources. The physical phenomena did not lend themselves to mathematical calculations, and experiments had to be pursued on a full scale, both as to current and voltage."

Additionally, underwater cables for long water crossings were needed. Frequency changes, asynchronous systems with the same nominal frequency, long interregional ties, remote load centers, and congested metropolitan areas were among the many considerations facing Lamm, according to IEEE Fellow Edward Wilson Kimbark in a 1971 publication. Nonetheless, after his brief compulsory stint in the Swedish Military, ASEA named Lamm head of its Rectifier Department in 1929. Lamm and his ASEA team pressed on to improve the HV mercury-arc ionic valve for commercial use.

In 1939, Lamm received a patent for grading electrodes in mercury-arc valves. The new technology considerably increased the peak inverse voltage that the valves could withstand, reported Kimbark, making them practical for transmitting large quantities of electricity over long distances. Impressed by his leadership and vision of the emerging HVdc technology, the Swedish State Power Board also gave Lamm and ASEA access to two power plants to test the developing valve in 1942.

Overcoming Distractions

An article by K. Wollard in the March 1988 issue of *IEEE Spectrum* further illustrates the potential distractions before Lamm, including working on his doctorate and receiving a Ph.D. degree from the Royal Institute of Technology in 1943 (his thesis was "The Transductor, D.C. Pre-Saturated Reactor"). Sweden was politically neutral during World War II, maintaining trade ties with Germany and other countries. Lamm spent the war-time years traveling on behalf of ASEA, Wollard reported, including trips to the patent office in Berlin.

After hundreds of changes to the valve, a world war, and completion of a doctorate, Lamm's vision was finally put to the test in 1954 when he rectified ac and inverted dc power for a 100-kV, 20-MW line from mainland Sweden to the island of Gotland. It was the world's first long-distance HVdc underwater cable system, reaching more than 60 mi.

In following years, Lamm's HV mercury-arc ionic valves were reportedly used in a number of other HVdc transmission projects, including across the English Channel between France and England, between the main islands of New Zealand, between Sardinia and

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Italy, and a connection between Denmark and Sweden.

Renaissance Man

Lamm was honored with many awards, including with the IEEE Lamm Medal, the John Ericsson Cold Medal, the Gold Medal of the Swedish Society of Inventors, the Gold Medal of the Royal Swedish Academy of Engineering Science, the Polhem Prize, and the Arnberg Award of the Royal Swedish Academy of Science. Twice married, with four children, he made southern California his residence in 1965. From 1967 to 1988 he served as an IEEE director at large. He was also a consultant to ASEA's president until his retirement in 1969.

Staunchly anticommunist and pro-free market, Lamm was outspoken on a wide range of issues, including political concerns about his native Sweden. Even so, Lamm's portrait hangs in Stockholm's Gripsholm Castle, along with other distinguished Swedes, including the king and queen of Sweden.

Over the course of his life, Lamm is reported to have written more than 100 opinion pieces, mostly for the Swedish press, on topics including society, education, economics, and technology. Of note was a 1968 article critical of "infantrocity" child raising, that drew criticism and praise for its frankness on parents "falsely allowing children to believe they are more mature than they are," according to reports. He also supported the U.S. involvement in the Vietnam conflict.

Innovation Lives On and Grows

Lamm died 1 June 1989 in Burlingame, California. However, his legacy for innovation and excellence lives on in the annual IEEE Power & Energy Society Uno Lamm HVDC Award. The first award was fittingly awarded in 1981 to Dr. Erich Uhlmann, known as the father of HVdc systems technology, and it continues to recognize outstanding individual contributions to HVdc technology.

Over the years, Lamm's visionary work has evolved to better serve the energy needs of the world. Today, the HVdc market widely relies on thyristors due to their ability to operate at high power levels. Thyristors are found across the globe in many HVdc installations with voltages up to 800 kV and power ratings approaching 8,000 MW.

The latest advancement in HVdc technology that furthers Lamm's work is found in the voltage source converter (VSC), which uses insulated-gate bipolar transistors (IGBTs) arranged into a unique topology. Examples of HVdc installations using IGBTs include the

TransBay Cable project, which was the first to use Siemens' modular multilevel converter topology, and the INELFE project connecting France and Spain utilizing two symmetrical monopoles, each with a capacity of 1,000 MW.

Work at ASEA

Lamm's early technological contributions can be traced back to when he was a young electrical engineer employed by ASEA. Founded in 1883 and later merged with a Swedish national electrical power company, ASEA was one of Europe's most important electrical production and distribution innovators for approximately 100 years. Today, it is an international holding company.

After receiving his master's degree and serving in the Swedish military, Lamm joined ASEA's training program in 1928. The young apprentice proved his worth that year, obtaining a patent to improve the voltage capacity on a mercury-arc valve. Biographical documents by W.R. Gould reflect, "His first assignments were in mechanical assembly in what today we would call the blue-collar sector of the work force. Here he learned 'hands on' the business of producing a product that had been conceived, designed, and planned by engineers."

Quickly moving up the ranks at ASEA's Ludvika manufacturing complex, in 1929 Lamm was appointed to ASEA's newly created Rectifier Department. The department would ultimately create the first HV mercury-arc valve and make modern HVdc transmission economically feasible. At the time, valves operated at 2,500 V, well below the level required to transmit large amounts of electricity. Over the next 20 years, Lamm and ASEA engineers worked to improve upon the three-phase ac used for power transmission.

In addition to his breakthrough performance on the HVdc Gotland project, Lamm worked on numerous projects that helped shape the world's energy and HVdc transmission future. In 1955, he organized the nuclear engineering effort for ASEA's Vasteras headquarters. He was also ASEA's representative on the board of directors of the Swedish state-financed Atomic Energy Company. During his tenure on the board, Sweden's first nuclear reactors went into commercial operation. In the 1980s, more than 50% of Sweden's electricity was provided by nuclear energy. However, political and environmental controversies ultimately led to Sweden's decision to phase out nuclear production.

In 1961, Lamm was appointed head of the ASEA team in the United States to build the Pacific DC Intertie. The transmission had the highest power, voltage, and strength of any ac or dc power line in the world, according to an article in *IEEE Power Engineering Review*.

This landmark achievement in dc transmission brought the technology to full maturity, according to reports. "It was also to be the high point in the use of mercury-arc technology—future systems would look to the emerging technology of solid-state, semiconductor, or transistor-type valves," according to Gould.

Published reports by Gould recall that Lamm's contributions to the success of the Pacific DC Intertie went beyond his technical expertise. "There were significant political problems, because the project involved entities of different regions of the western states and of different ownership format. In all of this Uno Lamm filled the role of technical consultant, political adviser, and peacemaker. While many individuals, corporate entities, and political subdivisions of government made notable and enabling contributions to the success of the undertaking, that of Uno Lamm was salient in its importance."

In 1970, Lamm led the move to replace the mercury-arc technology with semiconductors used in thyristor technology. "When William Shockley received the Nobel Prize for the invention of the transistor and applied this name to it, he was reported to have said that he had heard 'some Swede' use the word in a technical presentation and thought it aptly applied to his new discovery," Lamm biographer Gould stated.

Mercury-Arc Valve

The first mercury-arc valve rectifier was invented in 1902 by New York-born electrical engineer and inventor Peter Cooper Hewitt. The rectifier was used in electric railways, industry, electroplating, and HVdc power transmission. Over the next two decades, researchers in Europe and North America made modifications to the original design that converted ac into HVdc. In the 1970s, mercury-arc valves were largely replaced by new semiconductor technologies used in diodes and thyristors.

Today, most rectifiers use solid-state technology. However, before the 1960s and prior to the development of

HV solid-state devices, mercury-arc valves were widely used in nearly all HVdc applications. (See Figure 1.)

Origins

Early mercury-arc valve rectifiers took the place of expensive and inefficient ac/dc motor-generator sets that powered trolleys, subways, and industrial equipment. Mercury-arc valves typically were enclosed by a glass envelope holding a vacuum. But instead of being filled with gas like common cold cathode gas-filled tubes, the cathode was formed from a pool of self-restoring mercury located at the bottom of the envelope. As a result, the valves were much more durable and could handle higher currents than gas discharge tubes. Graphite rods, separated by glass to prevent arcing, were placed inside the glass envelope and served as anodes. The number of the anode arms varied depending on the application as well as the number of phases required, oftentimes one per phase.

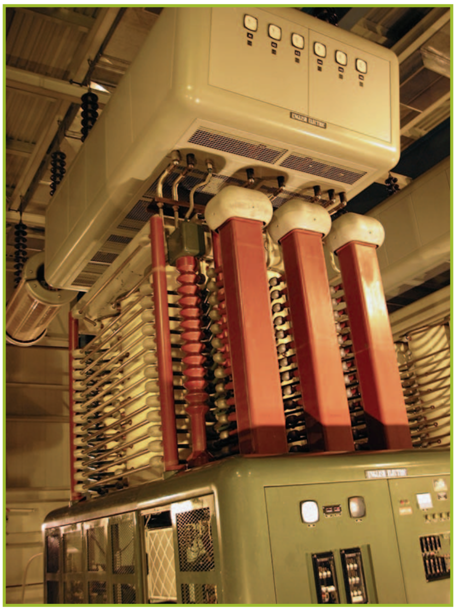

figure 1. A mercury-arc valve at the Manitoba Hydro Radisson Converter Station. (From Wikipedia, Creative Commons SA 1.0.)

How they Work

An HV arc between the cathode and electrode activated the mercury-arc valve, generally when the electrode connected with the cathode. A magnetic field was produced after the electrode was withdrawn from the mercury cathode pool, creating an arc. Free electrons emitted from the cathode triggered an ionization process within the mercury vapor. The mercury ions were drawn to the cathode, and electrons were attracted to the anode, producing the rectifying current that was injected into an inductive circuit. The mercury forming the cathode evaporated within the glass envelope during operation but quickly resettled back into a pool at the bottom when finished. The shape of the graphite-rod anode arms helped facilitate drainage back into the pool and avoided a conductive path between the cathode and anode (Figure 2).

Early Design Issues

Early mercury-arc valves were not without issues. Using mercury in fragile glass envelopes was a constant risk in the event that the glass envelope was broken. Reports indicate that a number of HVdc converter stations performed extensive mercury remediations to eliminate toxic buildups at the sites.

In addition, some mercury-arc valves were prone to "arc back," according to reports, where the valve conducted in the reverse direction when the voltage across it was negative. "Arc-backs can be damaging or destructive to the valve, as well as creating high short-circuit currents in the external circuit, and are more prevalent at higher voltages. One example of the problems caused by backfire occurred in 1960 subsequent to the electrification of the Glasgow North Suburban Railway where steam services had to be re-introduced after several mishaps. For many years this effect limited the practical operating voltage of mercury-arc valves to a few kilovolts," according to *Wikipedia*.

"The solution was found to be to include grading electrodes between the anode and control grid, connected to an external resistor-capacitor divider circuit. Lamm conducted pioneering work at ASEA in Sweden on this problem throughout the 1930s and 1940s, leading to the first truly practical mercury-arc valve for HVdc transmission, which was put into service on the 20 MW, 100 kV HVdc link from mainland Sweden to the island of Gotland in 1954," according to an article in *Wikipedia*. (See Figure 3.)

There would be ten more HVdc projects constructed after the Gotland HVdc link using mercury-arc valves. Further enhancements were made until the early 1970s when the last HVdc transmission site using mercury-arc valve was commissioned. At that point, blocking voltage of the mercury-arc valves could no long be increased.

Gotland HVdc

The Gotland HVdc link began operation in 1954, connecting Ynge on the island of Gotland, Sweden, to the mainland location of Västervik. The connection was made by 90 km of undersea cable. The Gotland HVdc link had a rating of 100 kV, 20 MW and was the first commercial HVdc in the world. This would be one of the many firsts for the Gotland HVdc project.

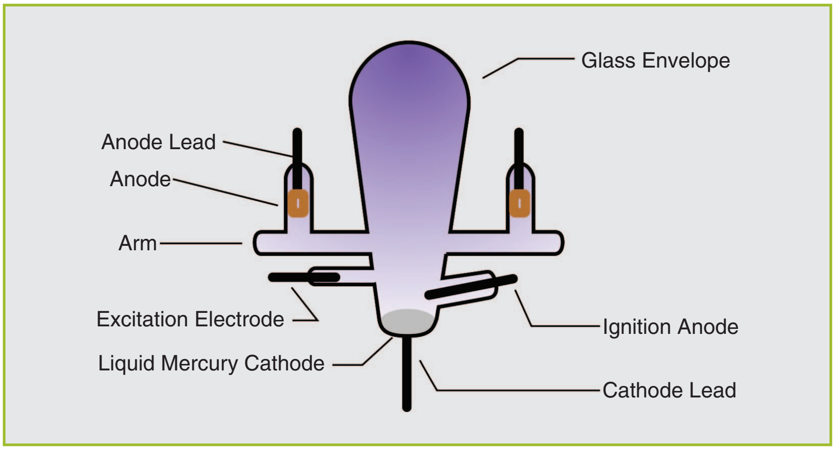

figure 2. A glass-envelope mercury-arc valve. (Image from Wikimedia Commons, in the public domain)

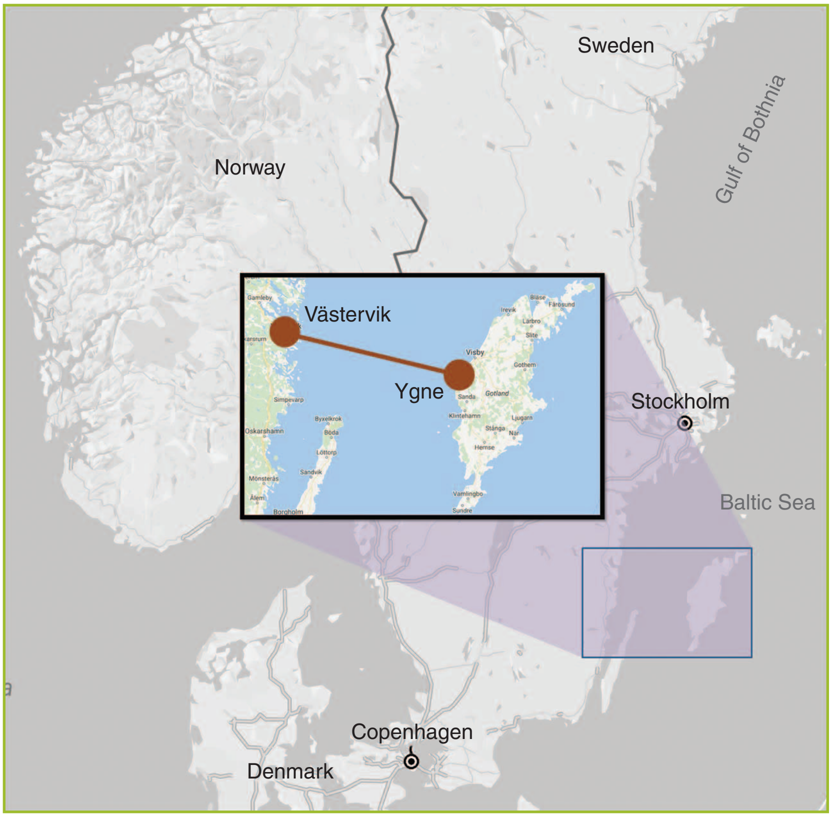

figure 3. The Gotland link. (Map image from Google–Map Data GeoBasis-DE/BKG.)

The inception of the Gotland HVdc project was led by Lamm's engineering and management skills. Finishing the development on the mercury-arc valves was essential to make the project a reality. Credit is also due to the Swedish State Power Board for being open to new technologies and choosing HVdc transmission for this particular application. The Swedish State Power Board also set up a test station with ASEA, enabling empirical development for the HV mercury-arc valves. A second station was constructed to accommodate more tests, ultimately helping to provide the resources necessary to finish the mercury-arc valve development.

Almost 15 years later, in 1970, thyristor valves were introduced to the Gotland converter stations and placed in series with the mercury-arc valves. The thyristor valves would be a cornerstone to future HVdc installations, and it was the first time they were used in a commercial HVdc link. This allowed the voltage to be increased to a possible 150 kV with a power capacity of 30 MW.

This would not be the first time the Gotland HVdc project would be upgraded. A second link, named Gotland 2, was constructed in 1983. An additional cable lay separate from the original Gotland link. It was entirely thyristor based and rated for 150 kV and 130 MW. It was a much larger capacity than the original Gotland HVdc project, allowing the island to transition its oil-fired power station and diesel to reserve.

Two more links would be constructed. One connected the island of Gotland with the mainland in 1985. The other connected the city of Visby to the southern part of the island in 1999. Gotland 3 was another undersea cable project designed to work together with Gotland 2 in a bipolar scheme but with the capability to operate independently. This doubled the power capacity to Gotland to a total of 260 MW. The cable and terminal equipment of the original Gotland HVdc scheme was dismantled after Gotland 3 was commissioned. The second HVdc link, called Gotland HVdc Light, was the first commercial HVdc Light project. (The HVdc Light name is the branded name of ABB for their VSC technology. The name HVdc PLUS is used by Siemens.) The VSC link used underground cables and had a rating of 80 kV, 50 MW.

Pacific DC Intertie

The Pacific DC Intertie project combined long ac and HVdc transmission systems to move electrical energy from the hydroelectric generators of the Pacific Northwest of the United States to southern California, approximately 900 mi away. (See Figure 4.)

The Pacific DC Intertie had one terminal, named Celilo, outside The Dalles, Oregon, and another terminal, Sylmar, north of Los Angeles, California. The initial ratings of the installation were 400 kV with a power capacity of 1,440 MW. The project was a collaborative effort between General Electric and ASEA of Sweden.

This HVdc link is notable with respect to Uno Lamm for two reasons. The first is that it uses the HV mercury-arc valves he developed. The second is more political and highlights Lamm's ability to bring ideas to fruition.

The idea to optimize the use of hydroelectric power from the Pacific Northwest by transmitting it to the southern part of California when there was an excess supply of power was nothing new and went back to the 1930s. It was considered again in 1961 when U.S. President John F. Kennedy pushed for a substantial public project that used HVdc technology. ASEA had already submitted a proposal a year earlier for an HVdc link with the Bonneville Power Administration that operated hydropower plants. The link would transfer power south to the Los Angeles Department of Water and Power.

To handle the transfer of technology from Sweden to the United States, a licensing agreement was ultimately made with General Electric. This was where Lamm flexed his political muscles. According to Wollard, "Lamm took on his opponents with equanimity, good humor, and an unassailable marshaling of facts. He testified before both houses of Congress, went to lunch with senators, and talked up the Intertie with ASEA's influential customers."

California's private power companies cited HVdc's technical hurdles as reasons why it would not be feasible. The power companies even hired a consulting firm to research and support their case. However, Lamm defended the technical merits of HVdc during an IEEE meeting in 1963 in New York.

Lamm continued to be actively involved in the Pacific DC Intertie, answering many technical questions about HVdc. He also instilled confidence in those who were uneasy about the new technology. The Pacific DC Intertie was commissioned in 1970. Combined with the ac transmission portion of the greater Pacific Intertie, it saved the electric customers in Los Angeles an estimated US$600,000 per day.

The Pacific DC Intertie, like the Gotland project, would be improved over the years and continued operating decades after commissioning. The Intertie was upgraded in 1985 to a capacity of 2,000 MW. During an expansion commissioned in 1989, a new 1,100 MW converter station was installed in parallel with existing stations, bringing the total capacity to 3,100 MW. The Sylmar converter station was upgraded on two separate occasions after damage from earthquakes in 1973 and again in 1994. The 1994 incident damaged the original mercury-arc valves, so a new 500-kV,

figure 4. A map of the Pacific dc Intertie. (Image from Wikimedia Commons, in the public domain.)

3,100-MW converter station was constructed that used much of the original station's equipment. Finally, the Celilo station was refurbished in 2016 and upgraded to 3,800 MW.

Developments in HVdc Technology and Where It Is Today

It is hard to say where HVdc technology would be without the contributions made by Lamm. He was at the forefront in developing the mercury-arc valve. He was also a key player in promoting the propagation of HVdc installations around the world. (See Figure 5.)

Early HVdc installations started with modest capabilities but quickly progressed over the past 60 years. The HVdc Gotland project in 1954, for example, was only 100 kV with a power transfer of 20 MW. In 2017, there are HVdc installations with up to 800 kV and power transfer capabilities approaching 8,000 MW, and even larger ones are planned for the future. Lamm's mercury-arc valve technology was superseded by the thyristor in the late 1960s, with the first completely thyristor-based HVdc project commissioned in 1972. The thyristor increased the availability of HVdc stations dramatically. The design was simpler compared to the mercury-arc valve. Maintenance was not as frequent, and less space was required for the same amount of rated power.

From 1954 until the first thyristor-based HVdc installation in 1972 (and coincidentally the last mercury-arc valve installation), the mercury-arc valve technology that Lamm spent 25 years developing had a lifespan of 18 years. The technology was used in 11 installations. As is almost always the case with new electrical breakthroughs, this first-generation technology (mercury-arc valves) was replaced fairly quickly with superior advancements (thyristors), but the mercury-arc valves set the stage for the capabilities of HVdc.

Put simply, a thyristor operates like a diode with an on switch, called the gate, that controls when the device conducts. The thyristor acts as a diode in the sense that when it is put into a forward bias state (the anode has a positive potential with respect to the cathode), it will conduct and allow the flow of current through the device once it has received a trigger from the gate. The trigger is a voltage applied to the device at the gate. When in a reverse bias state, the device does not conduct and blocks the flow of current. The drawback of the thyristor is that it only has the ability to be turned on but not off. The device cannot be put into a nonconducting state with an external signal as the nonconducting state is governed by the electrical flows of the network grid causing the device to become reversed bias.

The thyristor is still used prominently today. Many upgrades to the thyristor's capabilities have occurred since the 1970s when it was first used. It has earned its reputation as being reliable and mature in large power capacity installations in the thousands of megawatts.

The latest development in switching devices for HVdc technology is the IGBT. One key difference between thyristors and IGBTs is that IGBTs can be both turned on (conducting current) and off (blocking current flow) from an external control signal, whereas the thyristor can only be turned on. A thyristor must become reverse biased to be in an off state, and this is governed by the network grid and not directly controllable.

The IGBT takes the controllability of the thyristor and adds in the ability to turn the device off as well as on. This means its operation is fully independent of the network grid. Greater advanced control, the ability to reenergize blacked-out networks, and installations that have a smaller footprint are just a few of the benefits of IGBTs. In many ways, the IGBT is a superior device to the thyristor with the exception of power capability. The IGBT is still a relatively new device for HVdc and requires more research and development for

figure 5. A modern HVdc converter hall. (Image courtesy of Siemens, www.siemens.com/press.)

its power rating to increase. As mentioned previously, HVdc installations that use thyristors can reach capacities approaching 8,000 MW, whereas the largest commissioned HVdc installation using IGBTs is 1,000 MW per pole.

Patents

Lamm had more than 150 patents to his name. A search on the European patent office website yields about 120. The first documented patent on the website has a publication date of January 1931 with the title "Improved Means for Disconnecting Metal Vapour Rectifiers on the Occasion of a Reverse Arc." As discussed previously, the rectifiers were susceptible to a reverse arc (or arc-back), which can damage the valve. Lamm's patent outlined the use of a high-speed circuit breaker to disconnect the rectifier from the electrical network to help mitigate the potential damage.

This is just a small piece of the work performed by Lamm to improve mercury-arc valves for HVdc application. Some patents continued to focus on ionic valves while others targeted grid control and equipment protection. His patent application would continue for more than 40 years from his initial publication.

While the majority of Lamm's patents were submitted during his employment at ASEA, there are a few filed patents in the mid-1970s that show him as the applicant. These include a chlorinator system, an electrolytic cell, and a rotary piston engine. An interesting point about the chlorinator system is the length of the patent filing. While many of his patents were only a few pages long, the chlorinator system document is 44 pages. This goes to show that even after his pioneering days at ASEA, Lamm continued to share his ideas with the world.

For Further Reading

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