A Brief History of Direct Current in Electrical Power Systems

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***Abstract* — This article summarizes the history of the use of Direct Current (DC) in power systems, and various problems associated whit its commercial implementation.**

DC technology has been associated with power systems since the early uses of electricity; it has boomed and then fell into disuse in several occasions. This article aims to review the development stages of electrical systems where DC technology has been used, and also to analyze the reasons that led to its use, the advances that brought to DC technology, as well as the reasons that led to their subsequent abandonment.

Finally, is analyzed the new DC technology boom of recent decades and the promising development expectations that this technology brings to power systems.

***Index Terms* — History of electrical engineering, DC systems, HVDC Transmission, AC-DC power converters.**

I. Introduction

This article summarizes a brief history of the use of Direct Current (DC) in power systems, and the various problems associated with its commercial implementation. DC technology has been associated with power systems since the early uses of electricity; it has boomed and then fell into disuse in several occasions.

This article aims to show the causes that led to the evolution of electrical systems as are known today. To this end, the evolution of DC systems is presented since its beginnings to its replacement by Alternating Current (AC) systems as the standard for energy commerce, and the legacy left by these first DC systems that still persists to these days.

In the second section of this article the HVDC systems are presented as a natural solution to preserve the advantages of DC systems in the AC era. A brief summary of converter technology is presented since their application in HVDC systems dictates the way these systems have been implemented. Also, it's shown the evolution this technology has had and the main projects built around the world with the implementation of DC technology.

Previous works have shown an account of these projects [1-4] so this article follows and compliments this information with current data.

Finally, is analyzed the new DC technology boom in recent decades and the promising development expectations that this technology brings to power systems.

II. The Beginnings

The practical applications of electricity began with DC. The basic discoveries of Galvani, Volta, Ampere or Ohm were on DC [3]. The first widespread practical application was DC telegraphy, but electric lighting also began with DC powered by dynamos. First came carbon arc lamps operated in series at constant current and fed from series-wound generators. Later came carbon-filament incandescent lamps operated in parallel at constant voltage and supplied from shunt-wound generators.

The first electric central station in the world was built on Pearl Street in New York by Thomas A. Edison in 1882 [5]. It supplied DC at 110 V to an area roughly of 1.6 km in radius, and it had DC generators driven by steam engines (Fig. 1). Within a few years similar stations were in operation in the central districts of most large cities throughout the world.

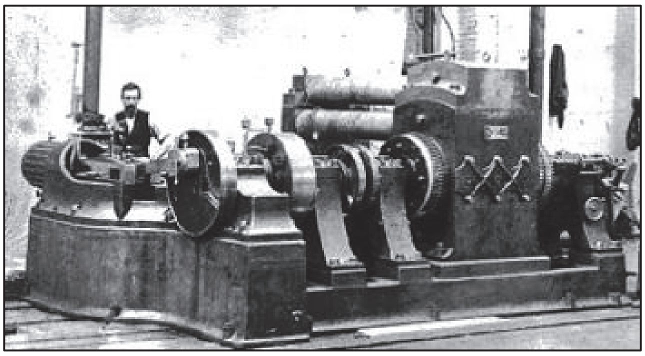

Figure 1. 100-kW engine-driven dynamo of the type installed at the Pearl Street station.

A. DC System Decline Causes

By the mid-1880s alternating current (AC) systems began to compete with DC systems. Inventors such as Nicola Tesla, William Stanley, Michael von Dolivo-Dobrowolsky, Elihu Thomson, Lucien Gaulard, John Gibbs, and others working in Europe and North America all contributed to AC technology.

In 1889, René Thury developed the first commercial system for high-voltage DC transmission in Europe, supplying Genoa, Italy from Gorzente River hydro turbines. The system was composed by generators in series to attain high transmission voltages. When loads were added to the system, other generators were added to maintain the voltage in the load.

In 1889, the first long distance transmission of DC electricity in the United States was switched on at Willamette Falls Station, in Oregon. In 1890 a flood destroyed the Willamette Falls DC power station. This unfortunate event paved the way for the first long distance transmission of AC electricity in the world when Willamette Falls Electric Company installed experimental AC generators from Westinghouse in 1890. In 1896, the first AC generation and transmission system was finished in the Niagara Falls using Westinghouse equipment [6].

This race between AC and DC systems was faced by great personalities of the time, in what would become the first standards war (Fig. 2) [7]. Much has been written about the so called "war of currents", but this conflict was more a media fight than a conflict that had real importance in the selection of the winning system. Final decisions on the type of system to be applied always ended up being based on technical reasons, and AC systems of the time offered greater advantages than DC systems given the needs and available technology of the time.

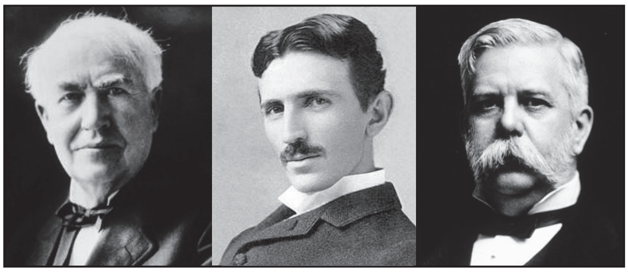

Figure 2. The three man faced in the first standards war. From left to right: T. Edison, N. Tesla and G. Westhinghouse.

N. Tesla's work contributed greatly to demonstrate the benefits of the use of AC systems, like the invention of the induction motor in 1888 [8]. Increasingly, promoted by industrialists such as George Westinghouse, the advantages of AC electric utility service became obvious, and by the end of the 19th century DC systems began an inevitable decline.

The advent of the transformer, tree-phase circuits, and the induction motor promoted the strengthening of AC electric systems as the world standard.

The transformer made possible the use of different voltage levels for generation, transmission, distribution, and use; particularly important for the high-voltage power transmission over long distances.

With the use of three-phase networks it was possible to ensure a smooth, non-pulsating flow of power and also bring an easy way to interrupt current on high-voltage equipment.

The induction motor is rugged, cheap, and serves the majority of industrial and residential purposes. Also, the advent of steam turbines, which are best at high speeds, gave a great advantage to AC generators since the commutators of DC motors and generators impose limitations on the voltage, size, and especially in speed of these machines.

The victory of AC over DC was almost complete. But some vestiges of DC distribution can be found in the electric traction system (trolley bus, railways or subway). Also, some cities continued to use DC well into the 20th century. For example, in Europe, Helsinki had a DC network until the late 1940s, Stockholm lost its dwindling DC network as late as the 1970s, and London had some loads on DC as late as 1981. In USA, certain locations in Boston still used 110 volts DC in the 1960s. In 2007, the last DC circuit, a vestige of 19th century DC system of New York City was shut down [9].

III. DC Aplication at the Beginning of the AC Era

Despite the general acceptance of AC systems, some people never forgot the obvious advantages of DC, so they proposed not to replace AC but to complement it with DC, introducing a DC link on AC systems. This is how the High Voltage Direct Current systems (HVDC) came about.

All HVDC systems are composed by four mains parts, as shown in Fig. 3:

Transformers: responsible for bringing the AC system voltage to values that are manageable by the converters.

Converters: are the devices that make the connection between AC and DC systems. A converter is basically an assemblage of controlled switches that commutes the different AC phases with the DC system as the AC phases vary. Therefore, the HVDC requires at least a converter at the sending end (called rectifier), and other at the receiver end (called inverter).

Conductors: the systems can be classified according the number of conductors they have: monopolar (with one conductor, usually of negative polarity), bipolar (with two conductors, one positive and other negative), or homopolar (with two or more conductors all having the same polarity, usually negative).

Protection and control: both always at the level of the converters which bring a high potential of control over voltage, current, power (active and reactive), and frequency.

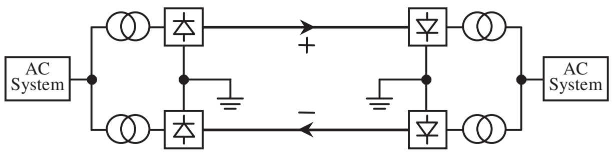

Figure 3. General scheme of a bipolar HVDC system.

The HVDC systems have many advantages over its AC counterpart, like:

- Greater capacity per equivalent conductor and simpler line construction.
- Each conductor can be operated as an independent circuit.
- Reduction of transmission losses and no skin effect.
- Improvement of the stability system.
- No problem with reactive power and voltage regulation.
- No Ferranti effect problems.
- No need of synchronous operation.

But also HVDC systems have some disadvantages like:

- Converters generate harmonics.
- Converters require greater reactive power.
- Converters have little overload capability.

Based on these advantages and disadvantages, many applications were found for HVDC, the most important are shown below:

- For transmitting large amounts of power over long distances.
- For interconnecting AC systems having different frequencies or where asynchronous operation is desired.
- For cables crossing bodies of water.

IV. Converters Evolution

The converters are one of the most complex and important devices in a HVDC system. Since a DC transmission scheme requires currents to be converted from AC to DC or vice versa, the feasibility and advantageousness of DC transmission depended on the development of suitable converters. The converters in a HVDC system have proved to be reliable but expensive. They also constitute a bottle neck to the power transmissible since valves have little overload capability.

A. *Firsts High Voltage Converters*

Three of the most serious attempts to develop a converter suitable to DC transmission are the transverter, the electrolytic, and the atmospheric-arc converter.

The transverter, developed by W. Highfield and J. Calverley in 1920 [10], was an electromechanical switch that consisted essentially of polyphase transformers commutated by synchronously rotating brush gear. It performed the three basic operations of voltage transformation, phase multiplication, and commutation, and could be used either as a rectifier or as an inverter. Several experimental transverters were built; the largest of which was rated at 2 MW 100 kV DC but none has been used commercially.

The electrolytic rectifier was patented by G. Carpenter in 1928 [11]. Based on an electrochemical method where two different metals are suspended in an electrolyte solution, and direct current flowing one way through the solution sees less resistance than in the other direction. Despite several attempts, this device was not produced for high voltage applications because of the low breakdown voltage and the risk of electric shock.

The atmospheric-arc converter, devised by E. Marx in 1932, is a switching device in which an arc between two like water-cooled main electrodes are ignited by a high-frequency spark between auxiliary electrodes in the path of the main arc, and is extinguished after a zero current by a blast of air that is continually released on the arc's path. A 5 km experimental line using atmospheric-arc converter was successfully operated in Germany with 16 MW and ±40 kV. The main difficulty encountered was that the main electrodes were consumed regularly requiring periodic replacement.

B. *Converters Applied Commercially*

The first converter technology that came to be applied commercially was the mercury-arc valves. It was based on early works of P. Cooper Hewitt in 1903 [12] but was U. Lamm in 1933 who develop a commercial high voltage mercury-arc valve [13]. A mercury-arc valve consists of an evacuated chamber containing a pool of mercury at the bottom forming the cathode. The anode is a carbon electrode at the top of the chamber. When the mercury pool is heated an arc can be struck within the chamber which conducts electrons from the cathode to the anode but not in the other direction. Hence, the device operates as a rectifier. The mercury-arc rectifier was used for power transmission and industrial processing between 1930 and 1975, when it was replaced by thyristor valves.

With the advent of the thyristor the converters evolution moved from electrochemical to solid state technology. It was developed in 1956 by engineers at General Electric (G.E.) led by R. Hall [14], but the firsts high voltage applications were in the middle of 1970s. The thyristor quickly replaced the mercury-arc valves as standards converters because of lower maintenance costs, simpler converter stations, and easier control system.

The thyristor is a silicon solid-state semiconductor device with four layers of alternating N and P type materials. They act as bi-stable switches, conducting when their gate receives a current pulse, and continuing to conduct as long as the voltage across the device is not reversed. In HVDC applications many devices are placed in series/parallel configurations to achieve the desired voltage and current ratings. The thyristor rectifier was used from 1975 to 2000 when it was replaced by Insulated-Gate Bipolar Transistor (IGBT).

IGBT is a three-terminal silicon semi-conductor device, noted for high efficiency and fast switching. The IGBT is a Voltage Source Converter (VSC), meaning that it can be switched off as well as on by gate control. This seemingly small difference has completely revolutionized the HVDC systems. The use of IGBT instead of thyristors is not a development comparable with the transition from mercury-arc valves to thyristor valves, but a rupture that required a complete change of the layout and design philosophy of the converter stations, and that greatly expanded the range of applications of HVDC. IGBTs allow the implementation of VSC instead of LCC. A main advantage of VSC converter stations is a high degree of flexibility: VSC has the inherent capability to control not only active but also reactive power.

The IGBT is a fairly recent development, first appearing in the 1980s. Third-generation devices were available in the late 1990s and quickly gained a reputation for excellent ruggedness and tolerance of overloads. In HVDC applications many devices are placed in series/parallel configurations to achieve the desired voltage and current ratings.

V. HVDC Projects Around the World

It's difficult to quantify how many HVDC projects there are in the world, mainly at the moment of delimiting what HVDC means. The scope of this work only quantifies the projects of a commercial nature (not developed with research purposes) that includes every element of a HVDC project previously (back to back projects are not included since they don't have conductors). Also, this work only refers to the beginnings of each project, future updates or extensions of a same project are not included. Finally, all the projects that have been in operation have been accounted for disregarding if they have been dismantled (projects under construction are not included).

There are 65 HVDC projects that interconnect power systems around the world [15]. Most of these projects are found in Europe (33.9%), Asia (32.3%), and America (24.6%), other projects have been built in Oceania (6.1%), and Africa (3.1%). Most European HVDC projects involve submarine cables, while Asia is dominated by overhead lines.

Although the commercial application of HVDC has existed since 1954, 58.5% of the projects have been developed in the last 20 years. This increase in the construction of HVDC systems in recent years is due mainly to the growth of the electrical network in Asia. Fig. 4 shows the distribution of the HVDC projects throughout the continents and how these have increased in recent years, especially in the Asian region.

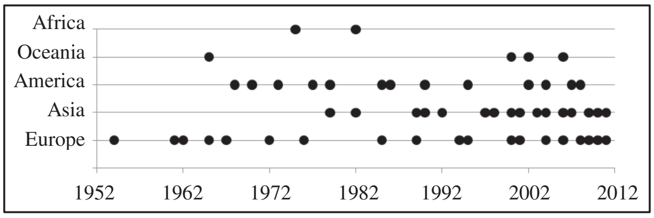

Figure 4. HVDC projects distribution.

In the manufacturing field of HVDC systems, the most important companies in charge of this task are ABB, Siemens, and Alstom. In the beginning, G.E. was an important manufacturer of HVDC systems, but in mid 1990s the HVDC division at G.E. was absorbed by Alstom. Other manufacturers like Hitachi, Toshiba, and BHEL, among others, have had an important role in the construction of certain projects.

The first HVDC applications were built using mercury-arc converters. The initiative in exploring the HVDC applications were taken by G.E., in 1936 they used a 27 km line with 5.25 MW and 30 kV to connect the Mechanicville hydroelectric plant with the G.E. factory in New York [16]. This line was also the first that proved a feature of HVDC systems: frequency conversion (from 60 Hz to 40 Hz). Although it is the first application of a complete HVDC system, it's not considered the first commercial application since it supplied the G.E. factory.

The Gotland I project is considered the first truly commercial HVDC scheme in the world. It was built by ASEA (now part of ABB), operated at 20 MW at ± 100 kV, and consisted of 96 km of underwater cable between Västervik and Ygne in Sweden. This site is the most significant heritage site in the development of HVDC systems because it showed the progress made by mercury-arc technology.

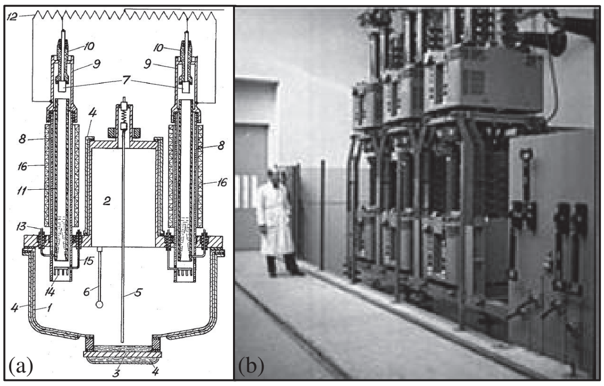

Figure 5. Mercury-arc converter diagram shown in Lamm's patent (a) that was also used in the Gotland I project (b)

In spite of the achievements of this project, HVDC did not immediately become a commercial success. Just until the 1960s more HVDC projects appeared. The most important of these projects was the Volgograd-Donobass Line [17] and was developed in 1965. It was a 473 km overhead line with 720 MW at ±400 kV built by the Russian government. It was the largest and with the highest voltages during these time.

During these years the Sardinia HVDC system was also built in Italy between Sardinia and the mainland [18], which was the first HVDC in the Mediterranean. It was a 413 km underwater cable with 200 MW at 200 kV constructed by English Electric (now part of Alstom). It was built in 1967 based on mercury-arc valves, but in 1993 it was upgraded with thyristor valves and it was added a third terminal towards Corsica, France, becoming the first multi-terminal HVDC system in the world.

In 1970 was built the Pacific Intertie overhead line with 1440 MW, ±400 kV, and 1362 km of length [19]. It was the first HVDC of USA and was built by G.E. and ASEA. After some upgrades, it now has 3100 MW and ±500 kV.

In 1975 was built the Cahora-Bassa overhead line with 1920 MW, ±563 kV, and 1456 km in length between Mozambique and South Africa [20]. It was the first HVDC system in Africa. This project was a breakthrough in technology for several reasons: it was the second to use thyristor valves (the first was the Kingsnorth in England, but had half the voltage and a third of the power), and it was built in cooperation by three important manufacturers: BBC (now part of ABB), Siemens, and AEG (now part of Alstom). The Cahora-Bassa was also the most powered, with the highest voltage, and longest HVDC system of the world for almost a decade until the construction of the Itaipu project.

Itaipu was built in Brazil in 1986 [21]. It was an overhead line with 3150 MW, ±600 kV, and 785 km of length built by ASEA. It was the first HVDC system in South America and was built in order to connect the Itaipu dam (the biggest hydroelectric dam between 1984 and 2008) to São Paulo city.

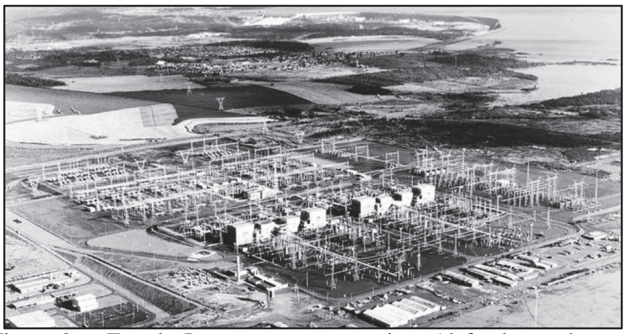

Figure 6. Foz do Iguaçu converter station. Al fondo puede verse the Itaipu hydroelectric plant.

The first uses of IGBT valves in high voltage were in 2000 in Australia. The project called Directlink was an underground cable with 180 MW, ±80 kV, and 59 km built by ABB [22]. This project demonstrated the great advantages in control that IGBT technology can bring to HVDC systems, but this technology is still limited to lower level applications.

The state-of-the-art in high level HVDC is the Ultra High Voltage DC (UHVDC), and the largest project in this area is the Xiangjiaba-Shanghai in China [23]. It was built by ABB in 2011. Nowadays is the most powered, with the highest voltage, and longest HVDC system of the world. It has 6400 MW, 800 kV, and 2071 km. Table I shows a summary of the most important HVDC projects to date. Figure 7 shows how the voltage levels of the projects have increased since Gotland to recent years.

TABLE I
SUMMARY OF MAIN HVDC PROJECTS

Project Name	Location	Year	Characteristics		
			MW	kV	km
Gotland	Sweden	1954	20	±100	96
Volgograd-Donbass	Russia	1962	720	±400	473
N. Z. Inter Island	N. Zealand	1965	600	±250	609
Sardinia	Italy	1967	200	200	413
Pacific Intertie	USA	1970	1440	±400	1362
Nelson River	Canada	1973	1854	±463	890
Cahora-Bassa	MZ-ZA	1975	1920	±533	1456
Hokkaido-Honshu	Japan	1979	300	250	167
Itaipu	Brazil	1986	3150	±600	785
Quebec-N. England	Canada-USA	1990	2250	±450	1500
Directlink	Australia	2000	180	±80	59
East-South Intercon.	India	2003	2000	±500	1450
Celilo	USA	2004	3100	±400	1200
Norned	NO-NL	2008	700	±450	580
Yunnan-Guangdong	China	2010	5000	±800	1418
Xiangjiaba-Shanghai	China	2011	6400	800	2071

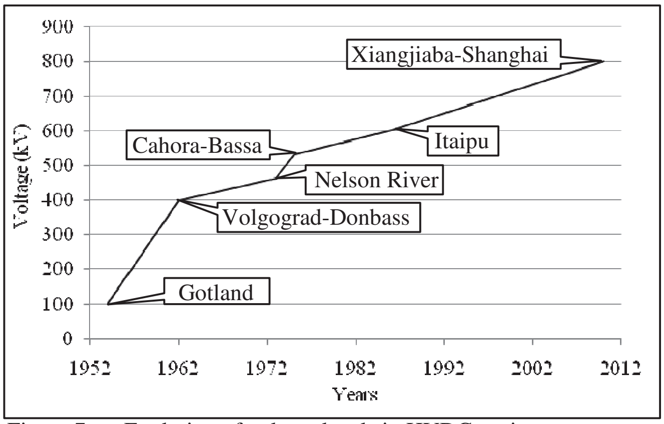

Figure 7. Evolution of voltage levels in HVDC projects.

VI. THE FUTURE

The growing needs of electrical systems, such as the load increases, the interconnection of large networks, the integration of renewable energy sources, and changes in operation and management of the systems, bring a high development potential for HVDC systems.

The coming years will see the construction of projects that will go over 2500 km in length, that will surpass 7000 MW or that will break the ±1000 kV barrier [24].

Throughout the world, projects are being planned that were unthinkable 15 years ago. These projects plan to connect large generation centers with megacities over thousands of kilometers. Like in China [25], Brazil [26], and India that expect to harness the vast hydroelectric potential they posses.

Another important reason for the undertaking of these projects is the connection of large electric markets, such as USA where it's planned to take advantage of price differentials between the three great markets of the region [27]. Also in Europe a major project is in development that aims to connect all electrical markets of the EU and also take advantage of the wind energy potential of the North Sea, creating a HVDC network with the largest underwater HVDC cables of the world [28].

Table II shows the most significant HVDC projects expected in the coming years:

TABLE II
SUMMARY OF MAIN HVDC PROJECTS UNDER CONSTRUCTION

Project Name	Location	Year	Characteristics		
			MW	kV	km
Rio Madeira	Brazil	2013	3150	±600	2500
Jinping-Sunan	China	2013	7600	±800	2090
Tres Amigas	USA	2014	5000	~300	~~
North-East Agra	India	2015	6000	±800	1728
NorthConnect	Norway-UK	2020	1400	~~	711

VII. Conclusion

In the early 20th century, AC systems were imposed over DC systems due to the benefits they offered and because these benefits could not be reproduced by DC systems with the available technology of the time. Some of these benefits have to do with the ease of changing voltages and current interruption.

These benefits allowed AC systems the transmission of energy over long distances, but with the growth of electrical networks, these AC systems are operated to their limit and DC systems have proven to be of great help to solve the problems that large electrical systems have, including distance limitations.

The natural descendants of DC systems of the early 20th century are the current HVDC systems. The HVDC systems have evolved considerably since their inception in the mid 20th century based on mercury-arc technology to become an ideal solution for large block transmission over long distances. This ensures a great future for the HVDC systems and a great development potential for large electrical systems.

The development of power electronics has enabled the growth that HVDC systems have had in recent years, and have helped to demonstrate the great value that DC systems have for modern networks.

As more than one hundred years ago, today's DC technology remains a fundamental part of modern electrical systems.

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