From Mercury-Arc to Hybrid Breaker

100 years in power electronics

2013 marks the centenary of ABB's involvement in power electronics. Power electronics have become ever-present in a vast range of applications ranging from large HVDC installations - transmitting gigawatts over thousands of kilometers - to everyday household devices. The development of power electronics was driven by the desire to convert electricity from one frequency or voltage level to another without having to resort to moving, maintenance-intensive mechanical parts. In the early days, converters used mercury-arc rectifiers, which were replaced by semiconductors in the 1950s and 1960s. Throughout its 100 year history, ABB has been a pioneer of both power electronic technology and its applications.

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The early years of the commercial use of electricity were marked by competition between different distribution technologies. Edison's DC vied with Tesla's AC in a battle that the latter ultimately won. Whereas many applications are well suited to AC, there are also uses for which DC remains indispensable, thus requiring a means of converting AC to DC. These applications include electrolysis (such as for the manufacture of aluminum), battery charging, wireless communications and the electrification of tramways, metros and some local railways. These applications are still an important part of ABB's business today. The list has since been extended with the addition of newer applications such as datacenters and HVDC transmission.

From an early stage in the development of electrical systems, inventors were seeking to convert AC to DC (rectification) and DC to AC (inversion), as well as to create variable output from fixed input (e.g. for variable-speed drives). Most power electronic applications today can still be placed in one of these three categories.

A precursor technology for AC to DC conversion was the motor-generator (a motor and generator fixed to a common drive shaft). The principle could also be reversed (for DC to AC conversion), or indeed used to convert between two different frequencies of AC. For example, several European countries electrified their railways at 16 2/3 Hz. The motor-generator setup could even be expanded for variable output applications.

One valuable property of motor-generators is their ride-through resilience. Short power interruptions are bridged by the kinetic energy of the rotating mass. It is interesting to note that this energy-buffering function is mirrored by DC-link capacitors in today's power electronic converters.

The drawbacks of mechanical converters include maintenance on moving parts such as lubrication and changing of carbon brushes.

Switching

Whereas motor-generators feature a complete galvanic separation of the input and output, power electronics achieve conversion by changing the current path at discrete moments through switching actions.

In its simplest form, the principle of path switching can be observed in the DC motor, where a commutator reverses the flow of current in the rotor winding in function of its position. Another more general-purpose AC-conversion is the contact converter. This converter features fast-moving externally-activated mechanical contacts (effectively an H-bridge, but with mechanical switches rather than valves). One notable weakness was that the waveform of the AC output was not a sine wave but a rectangle. This drawback was shared with many power electronic circuits. Overcoming this was to be one of the major points of progress in the area of modern power electronics.

Despite their apparent drawbacks, contact converters were able to fulfill current ratings beyond the scope of mercury-arc valves, and their production continued until the rise of silicon-based converters.

The mercury-arc valves

In the early years of the 19th century, the British chemist and inventor, Humphry Davy, showed that an electric arc could be created by passing current through two touching rods and then drawing them apart. A plasma (gas of ionized particles) forms in the gap between the electrodes and conducts current. The recombination of ionized particles in the plasma causes the emission of light, whereas the heat generated by the current creates new ions (excitation) and sustains the arc. It is interesting to observe that the underlying physics of today's semiconductor switches is equally concerned with the excitation, movement and recombination of charge carriers.

In 1902, the American inventor, Percy C. Hewitt, demonstrated a setup with one electrode made of mercury and the other of steel (carbon in later versions), enclosed in a glass bulb containing mercury vapor. An interesting property was that current would conduct from the carbon to the mercury electrode but not vice versa. Whereas the pool of mercury readily emitted electrons once the arc was ignited, the carbon anode did not to any appreciable extent (in the operating temperature range). The mercury vapor was ionized by the arc, and the bombardment of mercury ions onto the cathode generated sufficient heat to sustain its continued emission of electrons. The mercury-arc valve was born, and with it, power electronics.

In the following years, numerous inventors and companies sought to improve and commercialize this rectification principle.

Manufacture of mercury-arc rectifiers
In 1908, the Hungarian engineer Béla B. Schäfer began research on mercury-arc valves for the Frankfurt based company H&B (Hartmann & Braun). As H&B's main business was the manufacture of scientific instruments and the company had little experience with industrial high-current applications, a joint venture was created with Swiss-

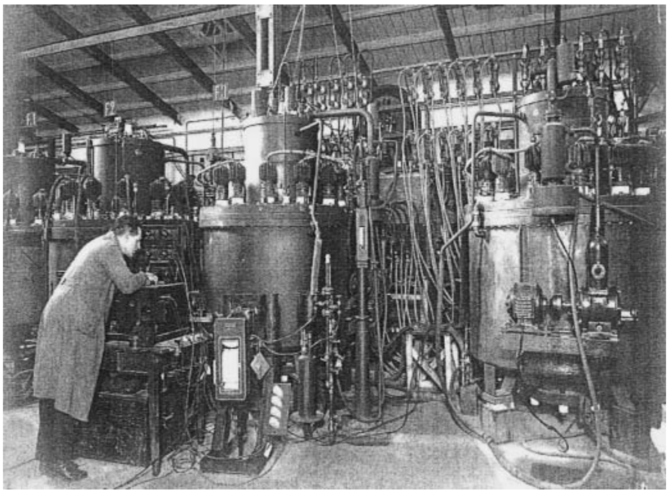

Figure 1: BBC production facility for mercury-arc rectifiers in Lampertheim, Germany (1921)

based BBC (Brown, Boveri & Cie) in 1913. The new company was called GELAG (Gleichrichter AG) and was based in Glarus, Switzerland. GELAG was mainly concerned with research and development, with BBC manufacturing the valves in Baden, Switzerland. In 1916, BBC also commenced production in Mannheim, Germany. In 1921, production was transferred to a larger factory in Lampertheim, Germany (Figure 1) and was joined by a second site that same year when BBC acquired the Berlin-based Gleichrichter GmbH (founded in 1919).

BBC took over H&B's stake in GELAG in the 1920s, and finally dissolved the latter in 1939, absorbing its activities into the parent company. Later, H&B also became part of ABB's heritage: The company was acquired by Elsag Bailey in 1995, which itself became part of ABB in 1999.

The first mercury-arc rectifiers were made of glass.
Due to the glass' low thermal conductivity and hence the restricted power capability, steel tanks were adapted instead with increasing power ratings. The market for mercury-arc valves boomed, and with it BBC's production (Figures 2 and 3). The company assumed a leading position in the development of the technology.

A simple rectifier circuit is shown in Figure 4. It is equivalent to an H-bridge in which a single enclosure with six anodes performs the function of six discrete diodes.

Whereas operation of such a valve could be sustained only under certain conditions, it could not start-up without aid. By providing a starting electrode, the ability to trigger conduction at an arbitrary point in time selective switching was made possible.

Starting in 1930, development of switchable valves began, enabling phase-fired controls (these valves fulfilled the same functionality that is today performed by thyristors - they can be switched-on arbitrarily but must wait for the current to reach zero to extinguish). By connecting them in an H-bridge, a line-commutated inverter can be made. As the term “rectifier” became increasingly incorrect in view of such new applications, in 1934, BBC began referring to its valves collectively as “mutators”.

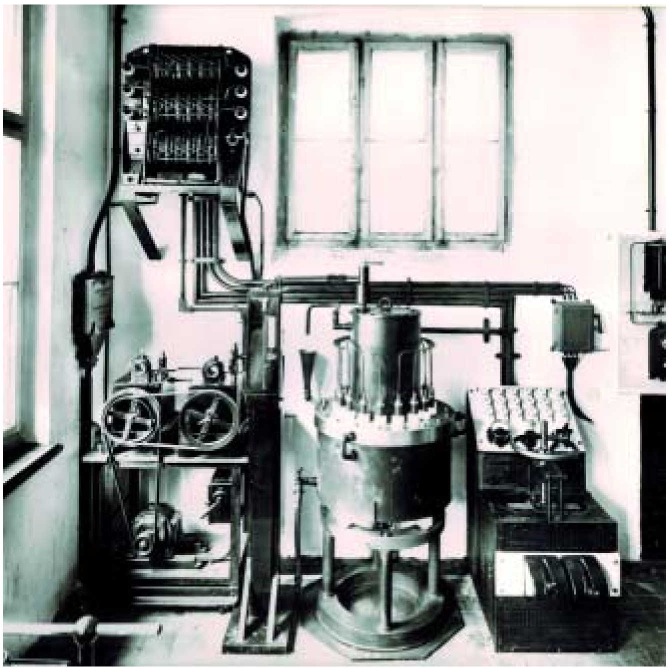

Figure 2: A BBC mercury-arc rectifier in the children’s hospital in Zurich, Switzerland (1914)

With both rectifier and converter functionality now feasible, BBC built a temporary demonstration line for the 1939 Swiss National Fair and Exhibition. The 500kW, 50kV DC link had a converter station at either end and transmitted electricity 25km from Wettingen to the company’s exhibition pavilion in Zurich using a single pole cable (Figure 5). This link was a precursor of today’s HVDC technology.

Figure 3 First locomotive using multi-anode mercury-arc rectifiers from BBC Mannheim, Germany (1938)

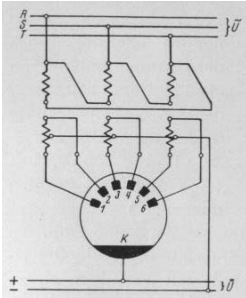

Figure 4: A simple rectifier circuit with a 6 anode mercury-arc rectifier equivalent to an H-bridge (Source: Wikipedia)

The manufacture of mercury-arc rectifiers continued until the mid-1960s. It was replaced by another revolution in power electronics: power semiconductors. Advantages of power semiconductors included greater power density and speeds, lower weight and losses as well as avoiding the toxic aspects of handling mercury.

The continuation will be published in the next issue of Bodo’s Power Systems in June 2013.

Figure 5: First HVDC transmission line Wettingen-Zurich, Switzerland. Pilot installation at the Swiss National Fair and Exhibition in 1939

Further reading

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