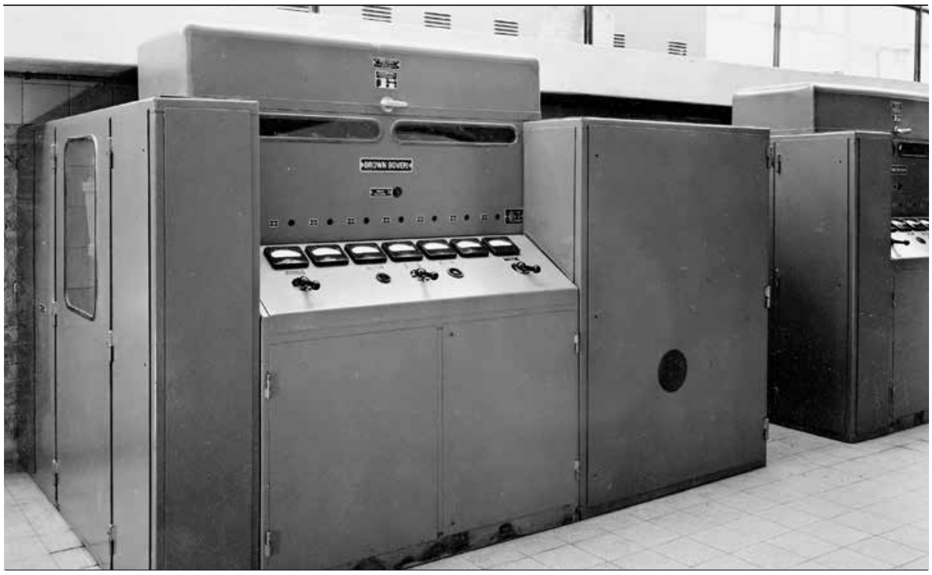
From mercury arc to hybrid breaker

100 years in power electronics

ANDREAS MOGLESTUE – 2013 marks the centenary of the involvement of ABB (and its forerunner companies) in power electronics. Power electronics have become ubiquitous in a vast range of applications ranging from large HVDC (high voltage direct current) 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 (and hence maintenance-intensive) mechanical parts. In the early days, converters used mercury-arc rectifiers. These were replaced by semiconductors from the 1950s and 1960s. ABB has, throughout this 100 year timespan, been a pioneer both of the technology itself and of its applications.

1 A BBC contact converter from the 1950s (rated output 5,000 kW at 200 – 500 V)



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 railways. These applications are still an important part of ABB's business today. The list has since been extended by the inclusion 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 creating variable output from fixed input (eg 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 equally be reversed (for DC to AC conversion), or indeed used to convert between two different frequencies of AC (several European countries electrified their railways at $16\frac{2}{3}$ Hz because this figure is precisely one third of 50 Hz). The motor-generator setup could even be expanded for variable output applications: For example the Ward-Leonard control uses the excitation of the DC generator to vary its output voltage (permitting, for example, a variable-speed drive). The Scherbius machine permits the connection of non-fully synchronized AC grids by allowing some phase slippage.

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 functionality is mirrored by DC-link capacitors in today's power-electronic converters.

The drawbacks of mechanical converters include maintenance to moving parts, such as lubrication and changing of carbon brushes, and the significant mechanical forces affecting construction and anchoring.

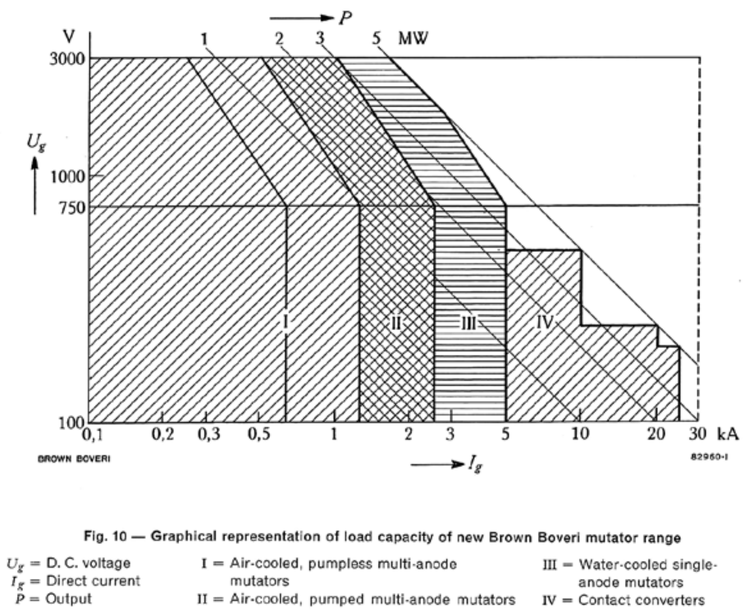
Converters relying on mechanical switches remained a maintenance liability. Power electronics set out to achieve similar results but without moving parts.

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 externally-triggered 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 (a simple DC to AC conversion). Another approach to a more general-purpose AC-conversion is the contact converter → 1. This converter features fast-moving mechanical contacts (effectively an H-bridge, but with mechanical switches rather than valves). One notable weakness was that, in contrast to motor-generators, the waveform of the AC output was not a sine wave but a rectangle. This drawback was shared with many power-electronic circuits. As will be discussed later in this article,

Title picture
A diode for traction applications (circa 1980)

2 Power ranges of different switchable BBC mutator types (and contact converters)



Source: T. Wasserrab, Mutator Meeting at Baden in 1955, Introductory Lecture (proceedings published by BBC)

3 An early mercury-arc valve enclosed in glass

ASEA built the world's first permanent and commercial HVDC link, connecting the Swedish island of Gotland to the mainland in 1954.

overcoming this was to be one of the major points of progress in the domain of modern power electronics.

Like motor-generators, converters relying on mechanical switches remained a maintenance liability. Power electronics set out to achieve similar results but without mechanical switches.

Despite their apparent drawbacks, contact converters were able to fulfill current ratings beyond the scope of mercury-arc valves → 2, and their production continued until the rise of silicon-based converters.

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.

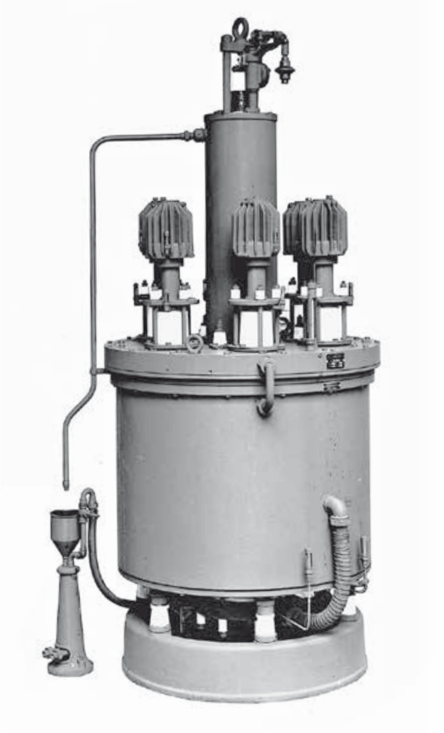
In 1902, the American inventor, Peter Cooper Hewitt, demonstrated a setup with one electrode made of mercury and the other of steel (carbon in later versions), enclosed in a glass bulb containing mercury vapor. An interesting property was that current would conduct from the carbon to the mercury electrode 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 mercury 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 commenced research on mercury-arc valves for the Frankfurt based company H&B (Hartmann & Braun). He registered the first of many patents in 1909 (his first patent was a solution to the challenge of embedding metal wires to cross the glass wall without compromising air-tightness). H&B was the first German company to supply a rectifier (delivered to a Frankfurt foundry in 1911). As H&B's main business lay in the manufacturing of scientific instruments and the company had little experience with industrial high-current applications, a joint venture was created with Swiss-based BBC (Brown, Boveri & Cie) in 1913. The new company was called GELAG (Gleichrichter AG) and based in Glarus, Switzerland. GELAG was mainly concerned with research and development, with BBC manufacturing the valves in Baden, Switzerland. In 1916, BBC also

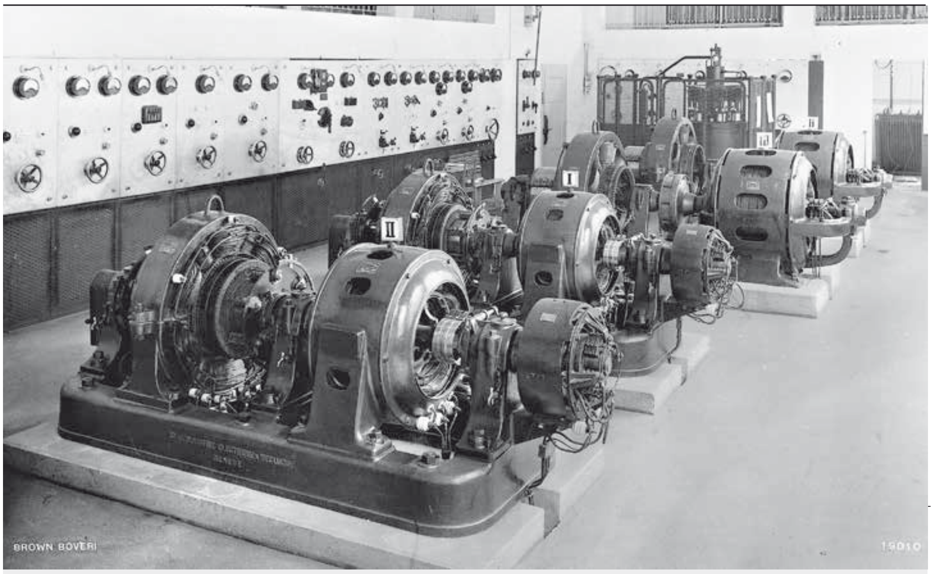
4 Steel tank mercury-arc valves from BBC



4a Type HG 5/6 valve (1923) (420 A, 650 kW, 1,550 V and weighing 1,700 kg) as used for the Zweilütschinen electrification ➔ 5.

4b A large mercury-arc valve in steel tank. This 2,500 A, 2,000 kW example from the 1950s weighed 1,235 kg and was more than 3 m tall.

5 Electrification of Bernese Oberland railway



The Bernese Oberland railway, in the Jungfrau region of the Swiss Alps, was electrified by BBC using 1,550 V DC in 1913. Rectification was performed by motor-generators, with the DC supply being supported by a battery. In order to demonstrate its mercury-arc rectifier technology, BBC added such an installation in 1920, with the rectifier working in parallel to the motor-generators. The demonstration impressed the railway with its high efficiency and reliability, remaining in service for 2¼ years. It was replaced by a permanent installation in 1923.

The photograph shows the converter station in 1924 with in the foreground the two main 220 kW motor-generators behind them the two auxiliary 48 kW generators with controllable excitation, and in the background the single 650 kW mercury-arc rectifier, showing their much reduced spatial requirements.

Source: The mercury arc rectifier plant of the Zweilütschinen substation of the Bernese Oberland Railway. Brown Boveri Review, October 1925, page 214.

Semiconductivity was first recognized in silver sulfide by Michael Faraday in 1833, but the phenomenon was not fully understood until the early 1930s.

commenced production in Mannheim, Germany. German production was transferred to a larger factory at Lampertheim, Germany, in 1921 and 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.

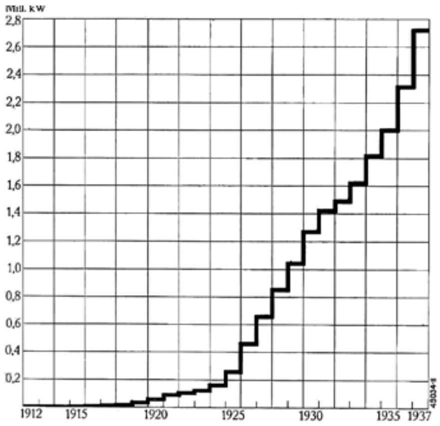
Schäfer left GELAG in 1921 and started his own consultancy. In 1927 he sold valve designs to ASEA (Allmänna Svenska Elektriska Aktiebolaget) for production in Ludvika, Sweden. Schäfer's expertise thus flowed into products of three of ABB's predecessor companies.

Valve design and applications

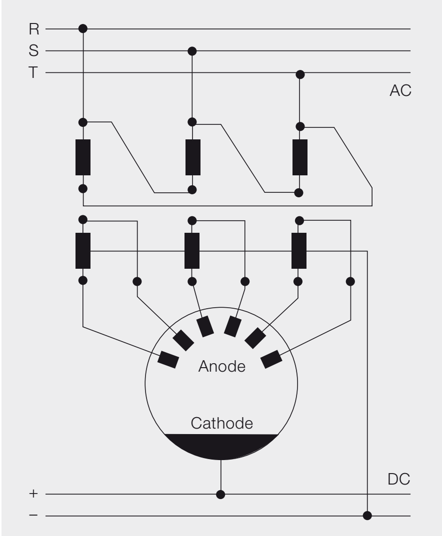
Due to the low thermal conductivity of glass, the power capability of a valve is restricted by its surface area ➔ 3. As power ratings increased, steel tanks (with isolated electrodes) were adopted instead ➔ 4. The market for mercury-arc valves boomed, and with it BBC's production ➔ 5–6. The company assumed a leading position in the development of the technology.

A simple rectifier circuit is shown in ➔ 7. It is equivalent to an H-bridge in which a single enclosure with six anodes performs the function of six discrete diodes.

6 The production of mutators was a rapidly growing business for BBC.



7 Mutator for rectification of three-phase AC



Whereas operation of such a valve could be sustained if the operating temperature was maintained within the limits and the arc was not permitted to fully extinguish, it could not start-up unaided when no plasma was present. A starting electrode (to which a high voltage pulse was applied) was thus provided to create the initial arc. The ability to trigger conduction at an arbitrary point in time had obvious potential for selective switching (the valves described in this article so far were all diodes). Development of such switchable valves commenced in 1930, 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".

With both rectifier and converter functionality now feasible, BBC built a temporary demonstration line for the 1939 Swiss National Exhibition and Trade Show. The 500 kW, 50 kV DC link had a converter station at either end and transmitted electricity 25 km from Wettingen to the company's exhibition pavilion in Zürich using a single pole cable → 8 (the return path being by earth conduction). This link was a precursor of today's HVDC technology.

It was ASEA, however, that built the world's first permanent and commercial HVDC link, connecting the Swedish island of Gotland to the mainland in 1954.

The manufacture of mercury-arc rectifiers continued until the mid 1960s → 9. Mercury valves were finally replaced by another revolution in power electronics: semiconductors. Advantages of semiconductors included greater power density and speeds, lower weight and losses as well as avoiding the toxic aspects of handling mercury.

Semiconductors

The elements of the periodic table are generally divided into metals and nonmetals. In their pure form, metals conduct electricity, whereas nonmetals (mostly) do not. There is however an interesting group of nonmetals that display intermediate levels of conductivity. These are the semiconductor materials, most notably germanium and silicon. Some hybrid crystals such as gallium arsenide and silicon carbide also have semiconductor properties.

Semiconductivity was first recognized in silver sulfide by Michael Faraday in 1833, but the phenomenon was not fully understood until the early 1930s when the band theory of conduction emerged.

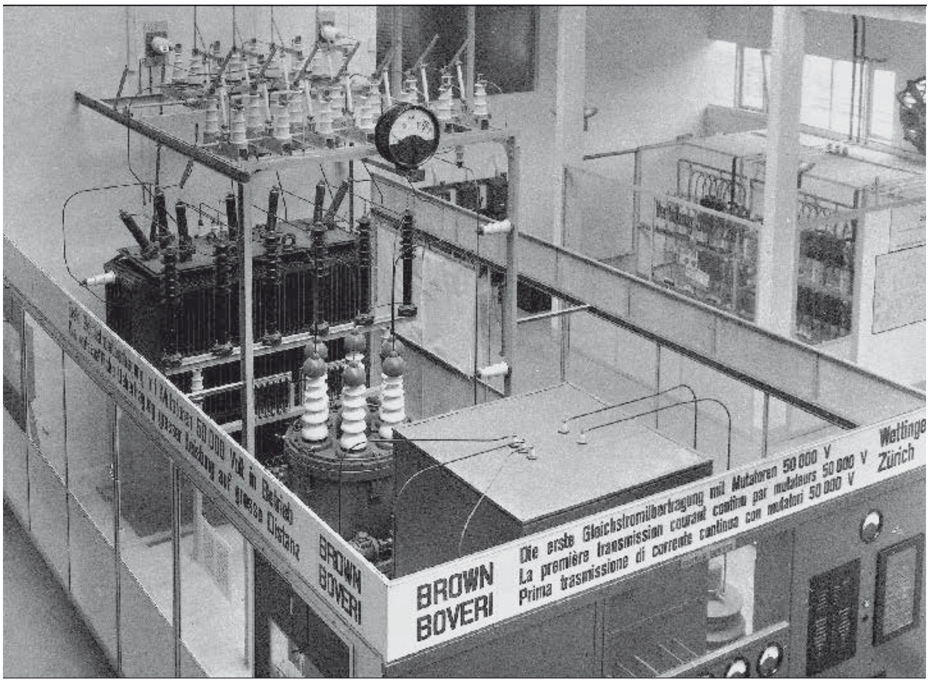
To raise the conductivity of semiconductor materials, impurities are selectively inserted into the crystal. These atoms occupy positions in the crystal lattice that an atom of the substrate material would otherwise occupy. If the inserted atoms have more electrons in their outer band than the host material (n-type), the "spare" electrons are free to move through the crystal and so increase its conductivity. If the inserted atoms have fewer electrons in their outer band (p-type), this creates so-called holes. Electrons from neighboring atoms are able to occupy these positions, which in effect leads to the holes themselves having mobility. Holes thus behave like positive charge carriers and also increase conductivity.

A simple example of a semiconductor device is a diode. A p-zone adjoins an n-zone on the same crystal. Current can flow from the p- to the n-zone (ie, in the p-zone holes flow towards the p-n junction, in the n-zone electrons flow towards the junction, with the two types of carrier recombining at the junction). If a reverse voltage is applied, charge carriers are depleted from the junction area and conduction ceases.

In order to create switchable valves, a method was required to externally trigger conductivity. The first transistor was created by Bell Laboratories in 1947. It used an electric field to control the availability of charge carriers in a germanium crystal, meaning that the current through it was determined by a control voltage.

The invention of the transistor kicked off a rapid and highly visible development culminating in the remarkable revolution

8 At the 1939 Swiss National Exhibition in Zürich, BBC demonstrated DC transmission using mercury-arc converters.



in communications and data processing, whose fruits (and ongoing developments) are highly visible today. Maybe less obvious but equally spectacular is another semiconductor revolution that occurred in parallel in the domain of power electronics: Today electricity can be transformed, controlled and converted in ways which only some decades ago would not have been considered possible. For example today's ubiquitous data and communications devices and their highly integrated microprocessor chips would be of little use without power-electronic circuits delivering their power, charging their batteries and keeping the datacenters and communications links running without which social networks and other online services could not function. Similarly, today's boom in renewable energy and the resultant reduction of emissions would not be possible without power-electronic converters assuring reliable and affordable grid connectivity.

It took many decades of development to make this feasible. Both BBC and ASEA commenced semiconductor development in circa 1954, with BBC's first rectifier diodes (rated 100 V, 100 A) coming onto the market in 1956. These and other early semiconductors were made of germanium[1], but the material was found to be unsuitable for power applications due to constraints in terms of blocking voltage and temperature. It was soon displaced by silicon.

Thyristor

Transistor applications in analog amplifiers (such as in radios and telecommunications) are well known. However, the demands of power electronics are different: Switches should ideally either be on or off, with the transition period being kept as short as possible. This is because the losses in the device, and hence the heat generated, are the product of the current and the voltage, and so either one or the other must be kept as close to zero as possible – both in the interests of energy efficiency and to prevent thermal damage to the device.

An early switchable power semiconductor was the thyristor, whose principle was proposed by William Shockley in 1950. A thyristor is similar to the p-n diode described previously, but with additional layers inserted between the outer p- and n-zones. These layers normally prevent conduction, but the injection of current at a third contact (called the gate) floods this area with charge carriers, enabling current to flow if a forward voltage exists between anode and cathode. Once triggered, the replenishment of charge carriers is self-sustaining, mean-

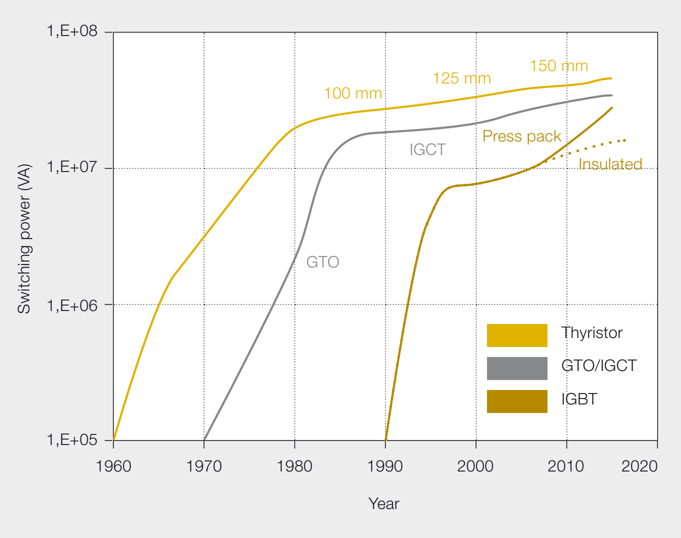
Footnote

1 Some manufacturers used selenium.

9 Milsestones of ABB's 100 years in power electronics

1913	BBC commences production of mercury-arc rectifiers in Baden
1915	BBC supplies stationary rectifiers to Limmattal Strassenbahn (tramway in Zürich area)
1921	Production commences in Lampertheim, Germany (BBC)
1924	Switching theory by Dällenbach and Gerecke published (BBC)
1928	ASEA commences production of mercury-arc rectifiers in Ludvika, Sweden
1938	BBC (Mannheim) equips locomotive with rectifier (experimental 50 Hz electrification in Germany)
1939	BBC demonstrates experimental DC transmission Wettingen – Zürich → 8
1954	First BBC germanium diode
1954	First commercial HVDC, Gotland link (ASEA)
1960	BBC's first thyristor
1961	HVDC link between Britain and France under English Channel (ASEA)
1964	First BBC locomotive with silicon diode rectifier (Re 4/4 for BLS), Switzerland
1967	First ASEA thyristor rectifier locomotive (Rc for Swedish Railways)
1970	Pacific Intertie, HVDC linking Celilo (Oregon) to Sylmar (Southern California) – the last major project to use mercury-arc valves
1971	Semiconductor manufacturing at Lampertheim commences (BBC)
1973	BBC opens research center at Dättwil, Switzerland
1979	HVDC link Cabora Bassa – Johannesburg (BBC in collaboration with AEG and Siemens)
1981	Semiconductor manufacturing at Lenzburg, Switzerland, commences (BBC)
1984	HVDC link Itaipu – Sao Paolo (ASEA)
1987	First BBC locomotives to use GTO converters (for BT and SZU, Switzerland)
1988	Merger of BBC and ASEA to form ABB
1993	Development work for BiMOS commences
1996	IGCT production commences
1998	BiMOS line opens in Lenzburg
2004	Three-gorges HVDC, China
2010	Acquisition of Polovodiče, Czech Republic
2010	New semiconductor factory in Lenzburg
2012	BIGT platform
2012	ABB announces hybrid breaker
2013	Work begins on new semiconductor reasearch facility in Dättwil
2013	ABB celebrates 100 years in power electronics

10 Development of switching power of the three major power semiconductor device types

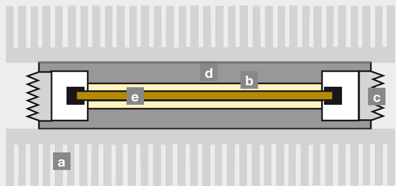


11 Lenzburg is the heart of ABB's semiconductor activities. The new BiMOS plant is the building on the right.

12 Semiconductor manufacturing in Lenzburg

13 Cross-section of a pressure contact device

In pressure contact modules, the load current enters through one surface d and leaves through the opposing surface. Low electrical and thermal resitances of the contacts are assured through high mechanical pressure on those surfaces.



a Heat sink
b CTE compensation (Mo)
c Housing (ceramic)
d Copper
e Semiconductor

ing the trigger current can be removed. Conduction does not cease until the current drops below a critical value. The device can thus be used for line-commutated inversion, but not for self-commutation (unless external components are used to artificially create a zero-crossing of the voltage).

Between 1960 and 1980, the maximum blocking voltage and power handling per device increased in a roughly linear fashion, from about zero in 1960 to 6,000 V and 600 kW in 1980 → 10.

GTO

Production of GTOs commenced in the mid 1980s. A GTO (gate turn-off thyristor) is a thyristor that can be turned off by applying a current to the gate in the reverse direction to that required to turn it on. The ability to produce devices that were able to switch off without an artificial zero crossing helped expand the scope of application of power semiconductors, enabling for example DC-DC converters and self-commutated inverters. Furthermore, multiple switching cycles during an AC half-wave can make the AC output less rectangular in shape. The width of current pulses is varied to modulate the desired waveform, hence reducing harmonics.

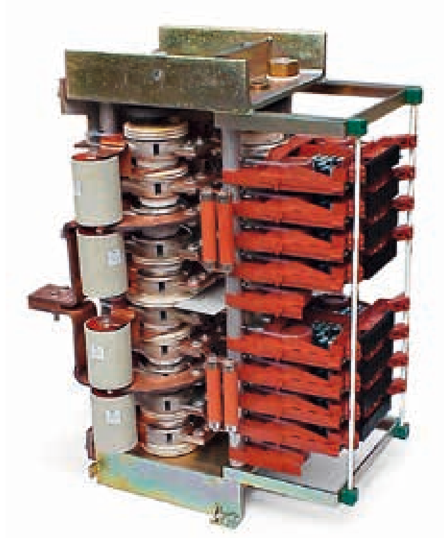
Semiconductor production

BBC's early semiconductor production was at Ennetbaden, Switzerland. BBC established a modern semiconductor factory at Lampertheim in the late 1960s, and sought to concentrate all manufacturing there. However, some of the production at Ennetbaden (mostly development activities and pilot production, but also modest levels of production) was transferred to Birr, Switzerland. These activities were moved to a new factory at Lenzburg , Switzerland, in 1981.

Following the merger of ASEA and BBC to form ABB in 1988, the Lampertheim site was sold to IXYS, and ASEA's factory at Västerås, Sweden, was closed, with all production being concentrated at Lenzburg. ASEA's strength lay in thyristors and rectifier components with negative bevel design, whereas BBC's strength lay in diodes, GTOs and thyristors. Although there was some overlap, the different ranges were largely complementary.

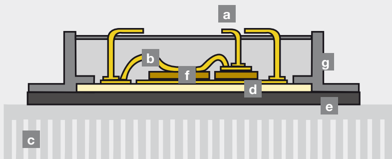
14 GTOs of different diameters

15 GTOs mounted in a stack with gate units and cooling elements



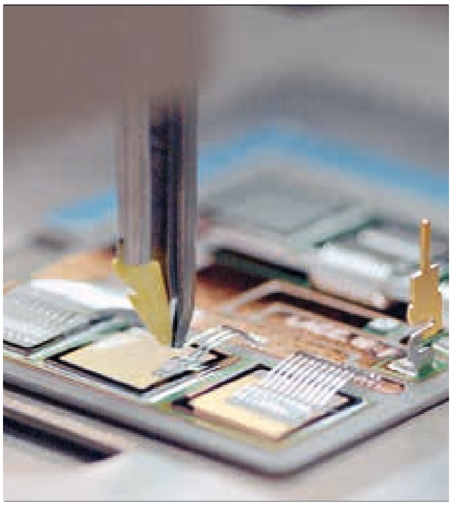
16 Cross-section of a Hi-Pak IGBT module

In insulated housing modules, the semiconductor f is galvanically isolated from the heat sink c. Electrical contacts within the module are provided by bonding wires.



- a Power and control connections
- b Bonding wire
- c Heat sink
- d Ceramic (usually AlN)
- e Base plate (usually AlSiC)
- f Semiconductor
- g Housing

17 Soldering of contacts to IGBT chips



At the time, semiconductor manufacturing was not recognized as a business in its own right within ABB, but was perceived as an activity for the support of other product areas, such as drives or HVDC. Product development and investment was thus largely driven by the needs of ABB's other businesses. All this changed rapidly when Anders Nilarp was appointed to lead ABB's semiconductor activities. He transformed the business into a standalone enterprise, directly competing with other semiconductor manufacturers on the outside market. His charismatic style also transformed the workings of the Lenzburg factory as he continuously sought to motivate and empower employees. In 1995, the Lenzburg factory was a finalist in the European Quality Award, and in 1996 it was awarded the "Supplier of the Year Award" by General Electric.

IGBT

Nilarp's greatest achievement was the new BiMOS factory that opened in Lenzburg in 1998, specifically tailored for the manufacture of IGBTs (insulated gate bipolar transistor). The introduction of IGBTs represented a fresh leap in terms of manufacturing complexity and the technologies involved, but at the same time also represented a step change in device performance and capability. An IGBT is a power semiconductor controlled by voltage rather than current – thus also reducing the power and space requirements of the gate units (the external drive units that turn the switch on or off via the gate), permitting more compact and lightweight converters. IGBTs are also more inherently stable than GTOs, reducing the need for protective circuitry, and are furthermore capable of faster operation, permitting higher switching frequencies.

IGCT

To also make hard-switching capability available for higher power classes, ABB pioneered the IGCT (integrated gate-commutated thyristor) in the mid 1990s. Developed on the basis of GTO technology, the new device was capable of much faster switching than conventional GTOs. In this it was supported by an integrated low-inductance gate unit. This development was remarkable as it occurred at a time that other manufacturers were withdrawing from GTO development, assuming the technology had no future.

ABB further strengthened its market presence with the acquisition of the Czech semiconductor company, Polo-

18 Hi-Pak IGBT modules

19 StakPak IGBT modules

vodiče, in 2010. This gave ABB a second manufacturing site (in Prague). At the same time, capacity at Lenzburg was again increased with the construction of a further factory → 11.

Manufacturing and design

The manufacture of semiconductors is a highly sensitive process. The silicon base material must be of a very high quality with extremely low levels of contamination. The insertion of the necessary p- or n-materials (doping) is a very precise process requiring the correct duration and temperature. Manufacturing thus occurs in so-called clean-rooms characterized by a carefully controlled atmosphere to keep contamination levels as low as possible → 12.

Most larger semiconductors (including thyristor, GTO and IGCT) feature a so-called free-floating housing. The silicon wafer is sealed inside a ceramic shell with copper contacts → 13–14. The contacts must be pressed against the silicon by a specified external force to assure optimal electric and thermal conductivity. To assure this force, devices are mounted in stacks → 15, with cooling units usually interspersed in the same stack. Devices are designed to short-circuit when they fail. A typical stack with series-connected devices will thus have some redundancy, permitting normal operation to continue until the next scheduled maintenance intervention.

The introduction of the IGBT marked a departure from this practice. Rather than using large area-wafers, IGBT modules feature larger numbers of small chips. Contact wires are soldered directly onto the chips → 16–18, eliminating the need for pressure-mounting in stacks and thus simplifying converter assembly while reducing weight and space requirements and making it easier to exchange individual modules during maintenance. However, IGBTs are also provided in press-pack housing for applications requiring such assemblies (StakPaks) such as for HVDC → 19.

BIGT

The latest development of the IGBT family is the BIGT (bimode insulated-gate transistor), an IGBT that integrates the reverse-conducting diode in a highly space saving manner (the BIGT is discussed more fully on pages 19–23 of this issue of *ABB Review*). The BIGT is an important component of one of ABB's most significant announcements of recent decades: the hybrid circuit breaker (discussed on pages 6–13).

The hybrid circuit breaker is a further example of semiconductors finding their way into entirely new uses. The range of applications of power electronics is growing in ways that only some years ago would have seemed unimaginable.

Contributions to this article by Björn Backlund, Jürgen Bernauer, Christoph Holtmann, Norbert Lang, Munaf Rahimo, Marco Rossinelli and Adriaan Welleman are gratefully acknowledged.

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Further reading

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