In harmony

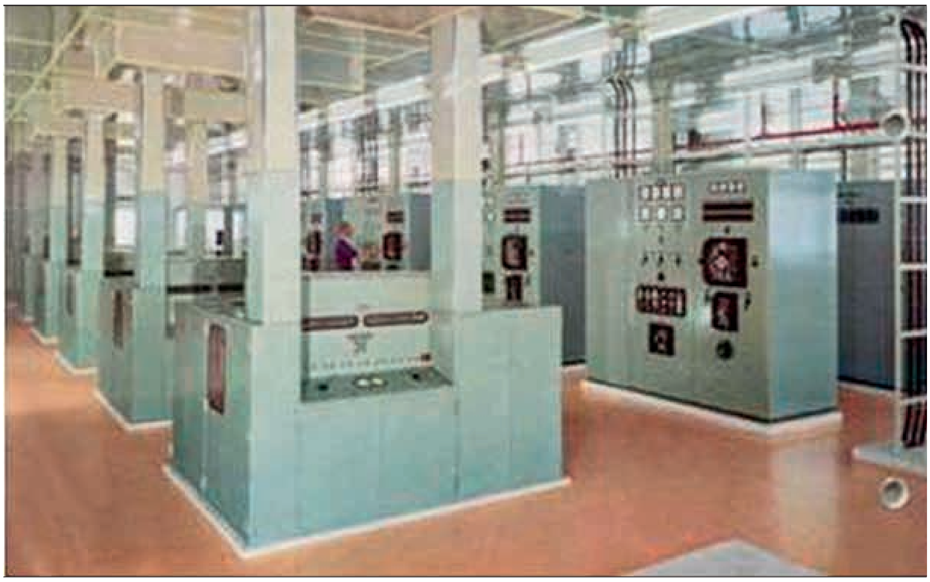
Looking back on a fruitful history of co-development of high power rectifiers and semiconductors

SHRIPAD TAMBE, RAJESH PAI – Although most electrical energy in the world is generated, transmitted and distributed in AC form, at utilization level many applications need DC. These include – but are far from limited to – electrolysis, steel making, traction and plasma torches. Power electronics support these applications in a reliable, dependable, economical and efficient manner. High power rectifier (HPR) development has been symbiotically linked to progress in semiconductor technology: The history of the two are thus best studied in conjunction. Both ABB's HPR and semiconductor technologies have evolved over a number of decades while achieving dazzling levels of technological progress. Today ratings in the hundreds of megawatts – unthinkable a few decades ago – are commonplace. In issue 2/2013, *ABB Review* visited the company's 100-year history of power electronics by looking at semiconductor technology and manufacturing. As part of the same celebration, the present article takes a different approach: It explores the development of power electronics from the perspective of ABB's HPR business.

Title picture
High power rectifiers have been an important part of smelting plants for many decades, and continue to fulfill this role today. This 2008 view shows the Boliden copper smelter (Sweden).

1 Mercury Arc Rectifier

2 Contact rectifier



The journey of invention and innovation that has been pursued in the domain of semiconductors for high power rectifier applications over the past decades from the origins of the technology to the devices available today is a remarkable one. And this progress is visible not only in datasheet numbers such as megawatts and kiloamps, but also in terms of safety and reliability, even under extreme operating or environmental conditions.

The primary goals of the BBC / ABB rectifier division has always been to build safe and efficient rectifier systems. The safety of the equipment but most importantly the safety of the people working with the equipment has been at the nucleus of all efforts and developments.

The origins of power electronics

Although developments in the field of power electronics over the last four decades years are symbiotically linked to progress in power semiconductors, ABB's predecessor companies were already active in power conversion long before semiconductor technology was commercially harnessed or even understood[1].

Mercury vapor rectifiers

Early rectifiers (starting around 100 years ago) used mercury vapor devices. They relied on the property of mercury vapor to block one polarity of AC current → 1.

Contact rectifier

AC to DC conversion was achieved by contact rectifiers. This technology supported conversion up to several kiloamps → 2.

The entry of semiconductors into rectifiers

The development of robust and high power semiconductors sparked a revolutionary change in the industry and created opportunities for numerous new applications. The elimination of the risks associated with mercury arc rectifiers and the high maintenance effort associated with contact rectifiers led to a rapid adoption of the new technology.

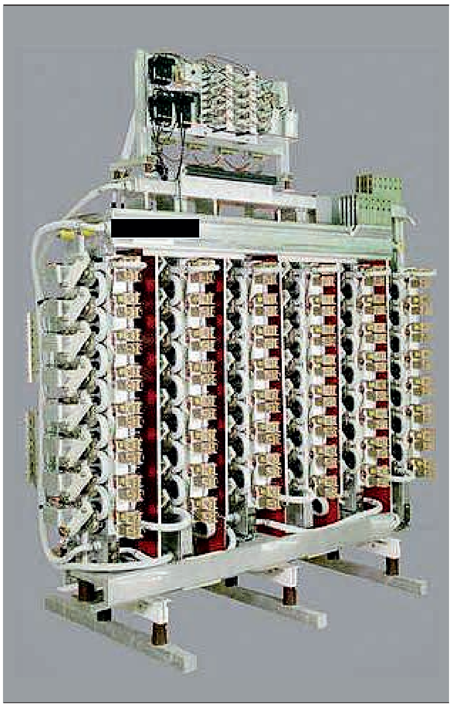
The ease with which semiconductors could be handled, with which heat could be dissipated, and with which series or parallel connection of devices could be achieved made them an indispensable part of countless applications.

BBC developed its first diode rectifier in 1956. This breakthrough was followed by the introduction of thyristors in 1960. In the following decade BBC developed pig tile diodes (glass and ceramic cylinder with bolts and flat bottom) for use in high power rectifier applications.

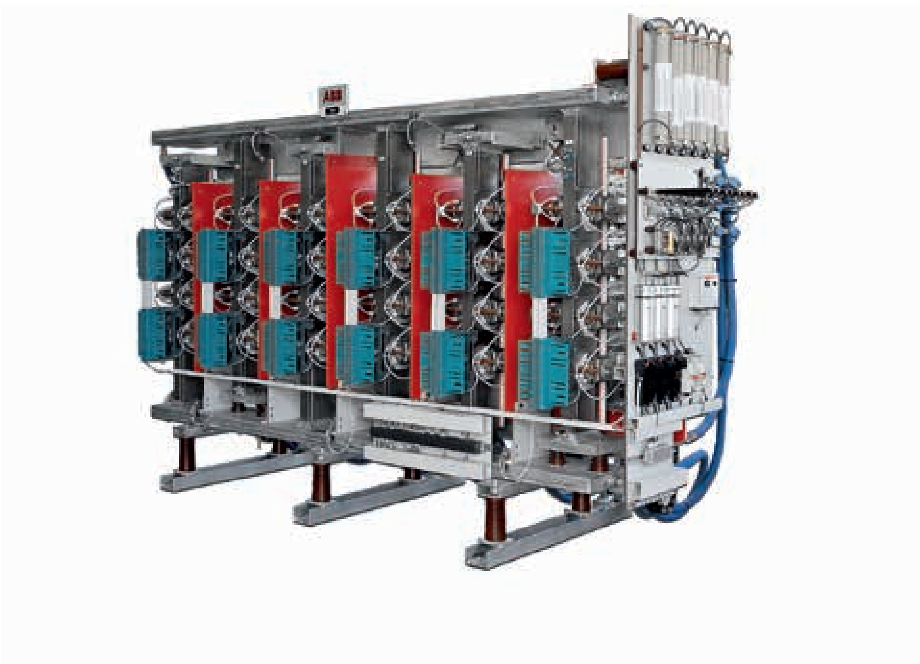
Footnote

1 See also "From mercury arc to hybrid breaker: 100 years in power electronics" in *ABB Review* 2/2013 pages 70–78.

3 Two inch thyristor rectifier



4 Four inch thyristor rectifier



The 1970s saw progress in wafer technology in semiconductor manufacturing and the subsequent development of 2" and 3" diodes and thyristors. These were the basis of a milestone breakthrough: BBC's development of the first diode rectifier plant with a DC current of more than 100 kA ➔ 3.

Today ABB builds rectifiers delivering up to 200 kA. This is possible due to the 4" diodes and thyristors ➔ 4 that are available with:
- Various blocking voltages
- Inbuilt explosion protection
- Low and consistent forward voltage drop (devices available in narrow band) for large rectifier units with 16 or more semiconductors in parallel.

Role of cooling medium

Despite the numerous advantages that semiconductors offered, it was the advent of the "press-packed" construction that proved to be the primary breakthrough to widespread use in high power applications. The main advantage of this construction was that it was highly efficient at conducting heat away from the silicon (heat being the main limiting factor of semiconductor performance and also the main cause of failure in operation).

The development of high power semiconductors and their applications is intrinsically linked with the development of the area cooling methodologies. This journey started with natural air cooled systems and progressed to using forced air cooled systems.

> A better and more reliable heat transfer helps secure a longer life cycle of the power conversion equipment

As current ratings increased, oil cooled systems were developed. As ratings rose further, the physical properties of oil increasingly became a challenge (namely its inflammable nature and changing viscosity). These physical shortcomings of oil as a cooling medium were banished with the introduction of water cooled and de-ionised water cooled systems. Today systems can be built with single unit delivering up to 200 MW.

Semiconductors: "The Heart of the Rectifier"

The semiconductor is one of the fundamental building blocks of today's high power rectifier systems. The matching of the semiconductor device (thyristor or diode) and the suitable fuse with the application depends on various factors such as:

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5 The RectiCal tool

RectiCal is equipped with algorithms, simulations and a database of various semiconductors and fuses that are validated by laboratory testing and site measurements. Rectical helps determine the:

- Size of the transformer
- Size of the rectifier including:
  - Semiconductor and fuse types
  - Number of parallel elements
  - Overload capability of the rectifier
  - Rectifier losses, ie, semiconductor and fuse loss
  - Cooling system requirement

- The rectifier application (aluminum smelting, copper or zinc electrolysis, DC electric arc furnace etc.)
- Rectifier output voltage and current
- Environmental conditions
- Grid conditions specially short circuit capacity
- Duty class and overload ratings

ABB's engineers are supported by a proprietary software tool called RectCal to determine the optimum sizing of the rectifier including selection of the semiconductors and fuses ➔ 5.

Life cycle and efficiency

Investment decisions are taken considering return on investment (ROI). Operational expenses are very important for economic viability. Most of the processes that ABB rectifiers serve have long life cycles. Hence purchasing decisions should not be based on the initial acquisition cost alone, but also on life-cycle costs.

Energy loss (or efficiency) is an important factor in regard to both operational expenses and satisfying environmental concerns and requirements.

The lifetime of the equipment and performance of the semiconductor can be greatly enhanced by the selection of appropriate cooling, mounting arrangements, contact stability between the surfaces transferring heat, current distribution and protection.

ABB has, for more than 80 years, been working to achieve longer equipment lifecycles coupled with high operational efficiency. The company has identified the following key issues as having a significant impact on the lifetime and efficiency of our products.

Mechanical assembly

The mechanical assembly that holds the semiconductors in place together with the heat sinks is designed to maintain a high pressure contact in order to secure a high degree of heat dissipation. A better, more reliable heat transfer helps to secure a longer life cycle of the power conversion equipment.

Current distribution

The cost optimization of a rectifier system requires a precise determination of the required number of semiconductors. For this, the current distribution through the semiconductor has to be resolved accurately. Such understanding of the converter not only optimizes cost but also helps better understand losses and supports the design of cooling system.

Protection

The risk of asset impairment can be minimized by implementing reliable protection against transient overloads and by isolating faulty semiconductors. This translates to longer life cycles. Even in the event of a semiconductor failure, containment and redundancy strategies mean there is usually only a minimum of inconvenience to the plant and often no damage to the rest of the equipment.

Explosion ring

ABB has patented technology that eliminates any kind of plasma spread in the event of semiconductor damage. Many incidents that could otherwise pose a risk of asset impairment are confined to the location of the damaged component. The explosion ring has a significant effect on the length equipment's life cycle.

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OVP (overvoltage protection)

One of the most common causes of semiconductor failure is voltage stress beyond acceptable limits. Harmful voltage transients often originate outside of the rectifier system. ABB's system design tools make it possible to provide very effective OVP considering various network aspects, process aspects as well as circuit breakers.

Fuse and semiconductor testing for explosion

Safe isolation of defective semiconductors can be achieved through blowing the series element fuse before the semiconductor reaches a state in which it can cause mechanical damage to itself and its surroundings. The demands on fuses in such applications are high. They need to be effective while consuming a minimum of energy as well as possessing sufficient body strength to withstand the heat generated during the fault. The withstand capability of ABB's semiconductor and fuse combinations are tested under the most sever conditions at ABB's power laboratory in Baden Switzerland.

All of these factors contribute towards achieving longer life cycles and safer operating conditions, and thus support customers in their quest for higher productivity.

Losses and their significance.

Losses in rectifier systems are mainly generated by the semiconductors and fuses. Fuse losses tend to be copper losses, but in the case of semiconductors the situation is different. Some semiconductor losses are proportional to current while others vary in proportion to the square of the current.

$P = I_t \cdot V_t + I^2 R_t$

I = Current through the semiconductor

V_t = Forward voltage drop across the semiconductor

R_t is the equivalent forward conduction resistance of the semiconductor.

Lower losses mean higher efficiency, which means lower operating expenses.

High voltage rectifiers (2,000 V_{DC})

Economy drives technology. Higher efficiency means better economic viability. It is shown that rectifier systems with higher voltages are more efficient than systems delivering the same power output using lower voltages. The reason for this is the fact that major losses increase with the square of the current and only proportionally to the voltage. ABB's reliable semiconductor technology with its capability to deal comfortably with higher voltages enabled the development of 2000 VDC rectifiers. This enabled HPR to offer significant improvements in operating efficiency through operation at higher voltages.

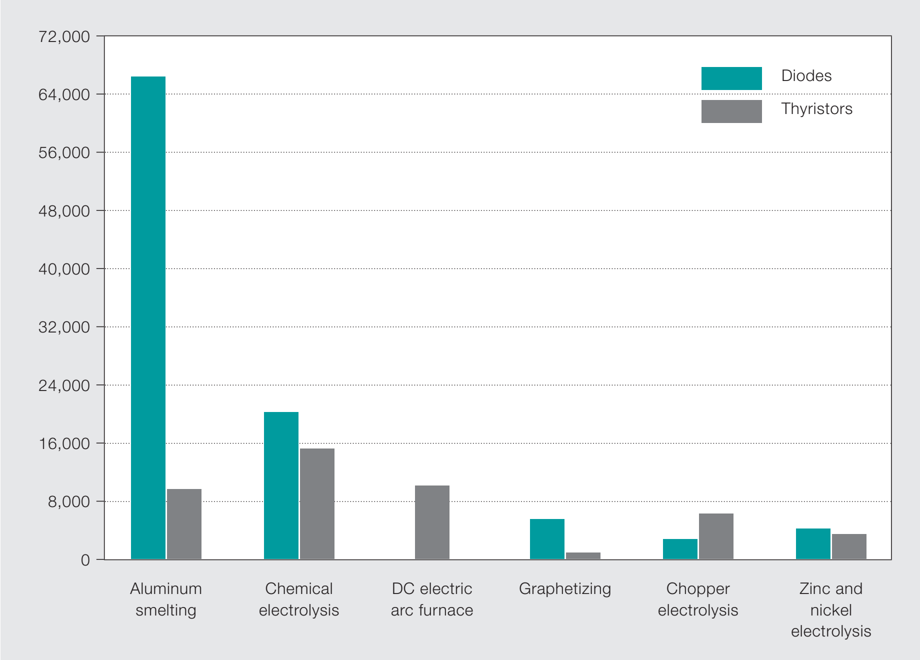
Milestone projects and change in trends

ABB is a technology leader in power electronics in general and in rectifier systems in particular. On its path of development, ABB achieved many milestones. The history of power electronics started with mercury arc rectifiers for research and industrial applications between 1913 and 1925. ABB's predecessor companies built the first HVDC link (1939) and the first commercial HVDC link (1954). In the late 50s, the companies that today make up ABB helped form the basis of today's diode and thyristor semiconductors.

In the journey of semiconductor development, around 1960 BBC developed contact rectifiers capable of up to 6 kA, which was considered a high current rectifier in that era. Rectifier ratings significantly increased between 1967 and 1980 with the emergence of what we now consider as high current and high voltage diodes. Between 1970 and 1980 converters for higher frequency applications (medium frequency heating and melting) and for HVDC established their own niche. These are just selected achievements from among the countless milestones spanning many fields of application. Over the years, ABB was behind the lion's share of breakthroughs in rectifiers for aluminum electrolysis and DC arc furnace applications.

The diode is the preferred semiconductor of the aluminum industry due to its simplicity of controls compared to thyristor-based systems.

6 Semiconductor usage in various HPR applications



100 years of power electronics

ABB's HPR group has been one of the bulk consumers of power semiconductors in ABB, and is proud to be part of the company's 100 year journey. Semiconductors have been used in HPR applications since the 1960s and the quantity of semiconductors used in different applications is testament to the significance of semiconductors to this area of activity → 6.

Aluminum smelting is one of the biggest contributors for the following reasons:

- Big rectifier systems with a large number of semiconductors in parallel
- Number of rectifier systems delivered and widespread and growing demand for aluminum
- Overload and redundancy requirements

The diode is the preferred semiconductor of the aluminum industry due to its simplicity of controls compared to thyristor-based systems. The development of diodes from 2" to 4" and the increase in blocking voltages helped further establish their usage.

Thyristors play an important role in building rectifiers for highly dynamic and demanding loads such as DC electric arc furnaces. Non aluminum electrolysis applications such as of chlorine, copper and zinc mostly employ thyristor-based rectifier systems for efficiency and controllability reasons.

Built for safety

Besides performance and reliability, safe operation has always been at the forefront of ABB's activities in power electronics. This covers the safety of people working with or near the equipment, as well as the protection of the equipment and adjacent installations. HPRs are designed to fulfill high reliability and safety demands, and where they do fail, they are designed to do so in the safest manner possible.

A technology that performs

Semiconductor elements (diodes or thyristors) play a vital role in the building of efficient, robust and reliable high-power rectifiers. As process technology progressed through the years, semiconductors were developed to meet the ever more demanding requirements of the rectifiers. The availability of larger size (4" and 5") discs with increased blocking voltages (4.2 kV, 6.5 kV) make very high power densities possible today.

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Further reading

S.Tambe, C.Winter and S. Dhareshwar, "Rectifiers for Higher Voltages in Aluminum Smelters – Challenges and Solutions", Metal Bulletin, 2007, Mumbai, India.