

The development of power electronics in Europe

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1 Introduction

Power electronics has a history that is much older than many engineers working in that field today usually realize. To provide a framework for this paper the following definition of the field seems to be helpful:

"Power electronics is the technology associated with the efficient conversion, control, and conditioning of electric power by static means from its available input form into the desired electrical output form."¹

In this way Thomas G. Wilson, Professor at the Department of Electrical engineering, Duke University, Durham, defined power electronics in an historical paper. Furthermore he described the purpose of engineer's effort:

"The goal of power electronics is to control the flow of energy from an electrical source to an electrical load with high efficiency, high availability, small size, light weight, and low cost."²

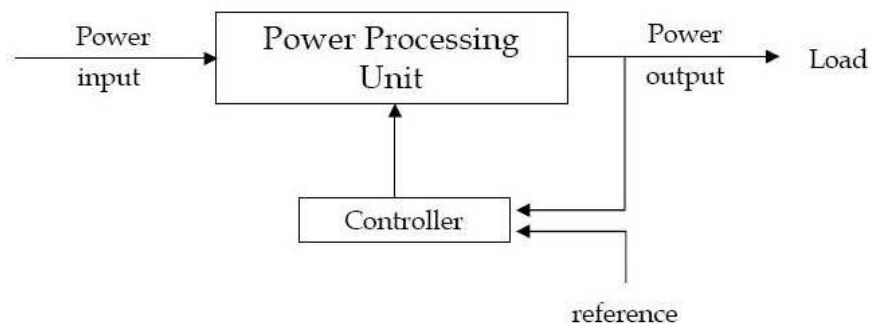


Fig. 1: Principle of the drive chain

Today power electronics systems are widely spread for adapting energy to the load in many different cases in industry, transportation, and household (Fig. 2), e.g.:

- Power supply and electrical transmission, e.g. high-voltage DC lines (HVDC)
- electric drives in electric cars, trams, locomotives and many other cases
- electric drives in conveying devices, rolling mills, machine tools and others
- power supply for welding, electroplating, and electrolysis
- power supply for consumer goods, e.g. switching-mode power supply for computers, TV and many other products, furthermore light dimming, speed control of fans, vacuum cleaners and many other electric appliances.

¹ Wilson, Th. G.: The Evolution of Power Electronics, in: Proceedings of the IEEE International Symposium on Industrial Electronics, 25-29 May 1992. Xian, China. New York, IEEE, 1992; vol. 1, pp. 1-9; p. 1

² ibd.

History in general and History of Technology as well has different methods to do historical research. On one hand historians of power electronics can investigate the development of central components, which are mercury arc rectifiers, gas-filled tubes, magnetic amplifiers, semiconductors, like transistors, thyristors, and – since a few years – smart power integrated circuits (IC). On the other hand in a history of science study one can describe the development of corresponding scientific knowledge. Since about 1960 the behavior of devices in control loops became more and more important. Furthermore the investigation of applications could be very interesting. Evidentially the development of power electronics is strongly interconnected with its applications in electric drives, welding, electroplating and electrolysis, power transmissions and many other applications/cases. Last but not least a study can focus on economic aspects including companies, the change of their shares of the market or governmental industrial policy.

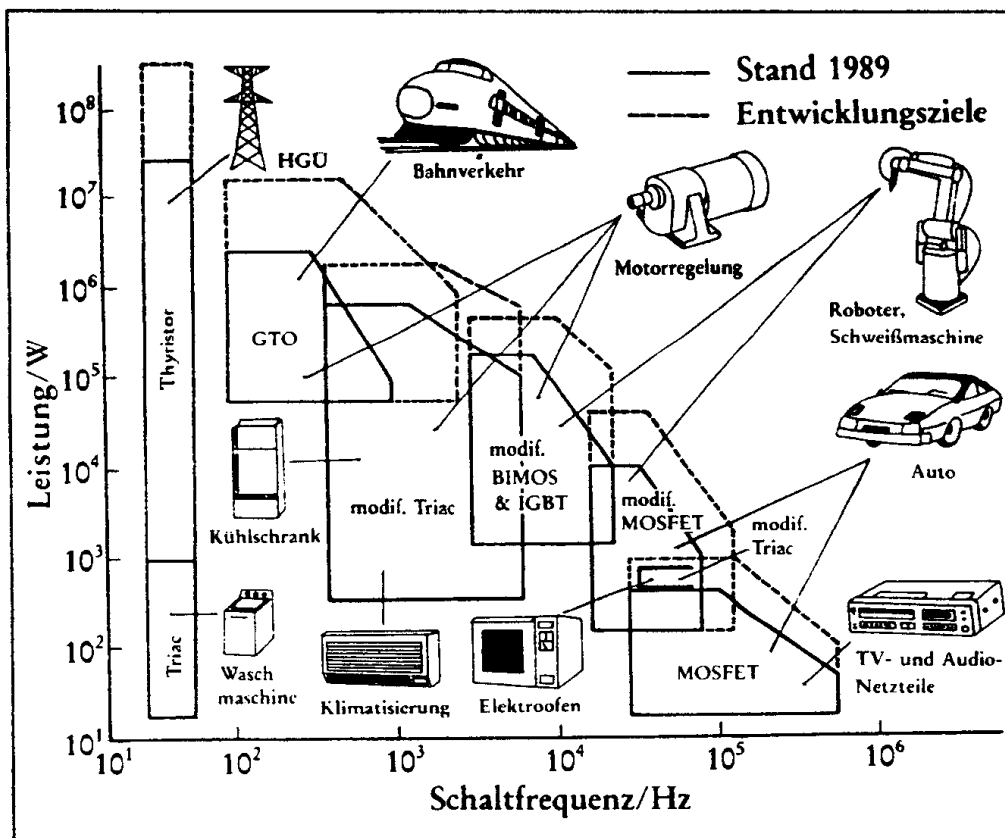


Fig. 2: Application of Power electronics solid-state devices, 1989
(Leistungshalbleiter im Aufwind, in: Physik in unserer Zeit 22, 1991, No. 5, p. 192)

In technical sense history of power electronics can be discussed from two points of view: the perspective of devices and the perspective of principle circuit diagrams. Whereas the history of diagrams can be regarded as a more or less continuous way starting with the first rectifier – the commutator of the DC generators invented by Hippolyte Pixii in 1832 – until recent inventions in the field of switching-mode power supply with integrated solid-state devices. A view in history shows evidently that a lot of circuit diagrams of inverters and AC-converters had been developed and realized first time mechanically or with mercury arc valves. However for technical and economic reasons such solutions spread out after solid-state devices had been available. In contrast, the history of valves is

characterized by parallelism and discontinuities (Fig. 3). This story starts with the invention of mercury arc rectifier around 1900 and leads to the smart power IC's today.

This paper deals with the history of valves and its applications in which the attention focuses on the development of mercury arc valves between 1900 and around 1950 and applications used in industry and transportation. At the 1930s and 1940s power electronics systems were single – almost unique – installations which served often for gaining experiences.

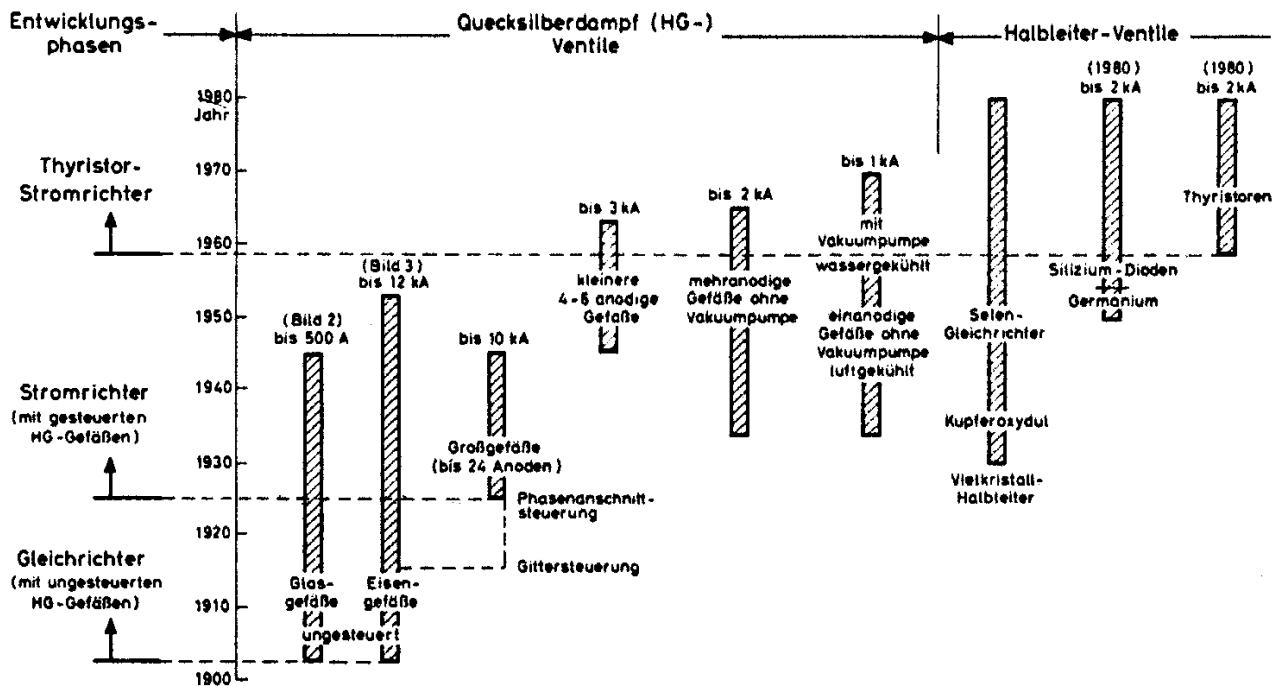


Fig. 3: Development of central devices (Schmidt; Schröder: Vom Quecksilberdampfgleichrichter zur Leistungselektronik, in: ETZ 101, 1980, No. 16/17, pp. 955-960; p. 955)

2 Mercury arc rectifier

The industrial rectifiers have its origin in the USA. In the late 1890s Peter Cooper-Hewitt, an American electrical engineer, invented an arc lamp working with mercury vapor (Fig. 4). The vapor was enclosed in a glass bulb. Soon he realized that this lamp conducted electricity only in one direction, which meant it operated as a rectifier. In 1902 Cooper-Hewitt designed a reasonable working mercury arc rectifier and received as well a German patent. The valve works in the following way (Fig. 5): In a glass bulb a mercury cathode sends out electrons whereas steel electrode almost no electrons emits. Because the current flows only in one direction the valve can be used as a rectifier. Higher current ignites an arc between the both electrodes. In rectifiers with more than one anodes this arc serves as a commutator jumping from one anode to the next.

In 1902, Hewitt and George Westinghouse formed the Cooper Hewitt Electric Company to manufacture and to sell the new lamps. Soon the company produced as well rectifiers. Far-reaching patent claims blocked the development of mercury arc rectifiers for about five years outside the company. Because of that, at first it only got advantages from the expanding market of rectification systems. This happened around 1900 because since the 1890s the implementation of power supply with single- and later three-phase current

created the problem of providing existing DC systems often erected already in 1880ies. On one hand some processes need DC in principle, e.g. electrolysis or recharging accumulators. On the other hand as well for economic reasons it was impossible to replace very quickly all existing DC networks with AC systems. Furthermore the DC motors had a much larger range of speed variation than other speed controlled drives at that time. Therefore DC motors were common for drives. This situation led to an increasing market for systems able to transform AC into DC.

PETER COOPER HEWITT IN NEW-YORK.
Elektrische Lampe mit leitender Gas- oder Dampfsäule.
Patentiert im Deutschen Reiche vom 26. Juni 1900 ab.

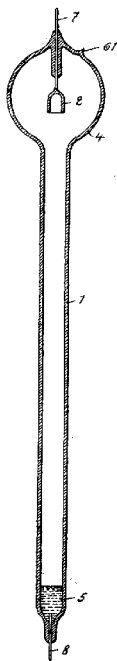


Fig. 4: German patent of the mercury arc lamp, 1900

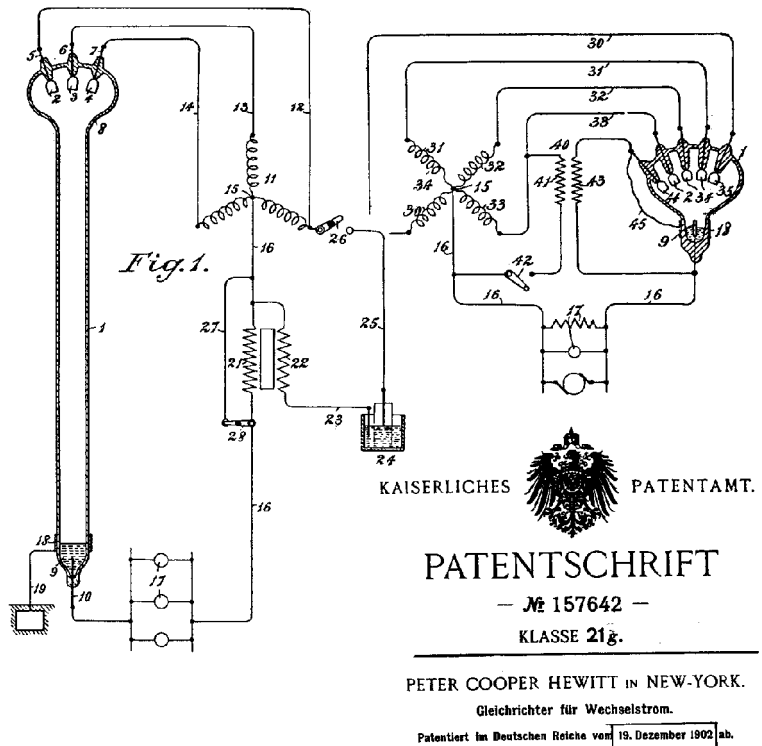


Fig. 5: German patent of the mercury arc rectifier, 1902

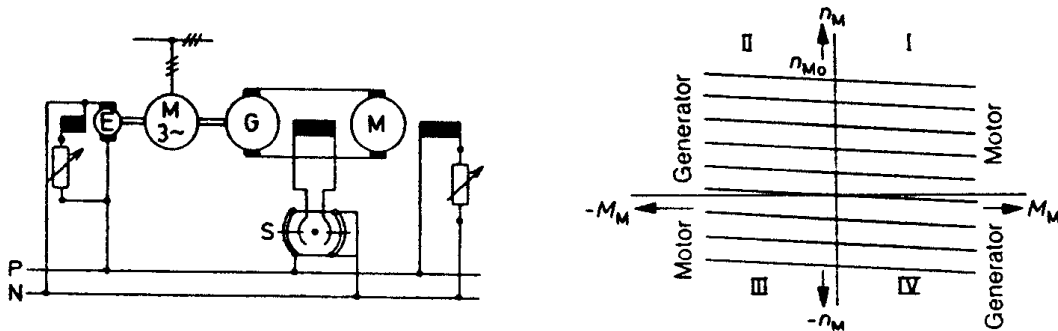


Fig. 6: Motor-generator system Ward Leonard with characteristics

To solve this problem engineers usual coupled an AC motor with an DC generator. In 1891 the American inventor and entrepreneur Harry Ward Leonard improved the classic combination (Fig. 6). A three-phase AC motor drives a DC Generator which supply a DC motor. Speed regulation could be reached very easily by changing the generator's exciting

voltage. Additionally this system allowed as well to give back energy on the network, that means that the generator can serve as electromagnetic brake. In fact with the around 1900 invented mercury arc valves a potentially competitor appeared but it took several years until the new technology became really a rival product for rotating converter. Motor-generators were still used until many years after World War II.

Around 1905 the glass valves got its typical shape: It looks like a pear with a big cooling space for condensation of mercury and several anodes in separate tubes (Fig. 7). At first the anodes consisted of steel, later of graphite. Platinum wires melted into the glass bulb connected the electrodes with components outside.

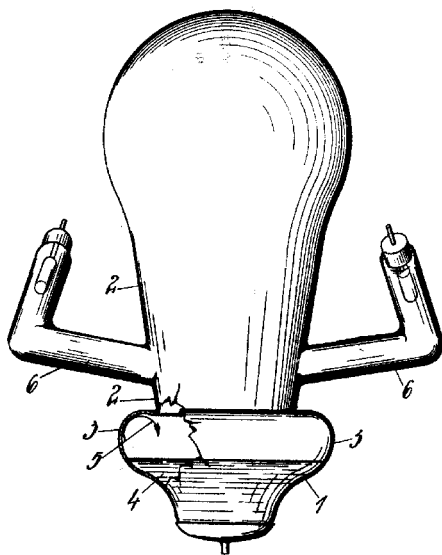


Fig. 7: Rectifier with glass bulb

Fig. 8: Iron vessel rectifier invented by Bela Schäfer



PATENTSCHRIFT

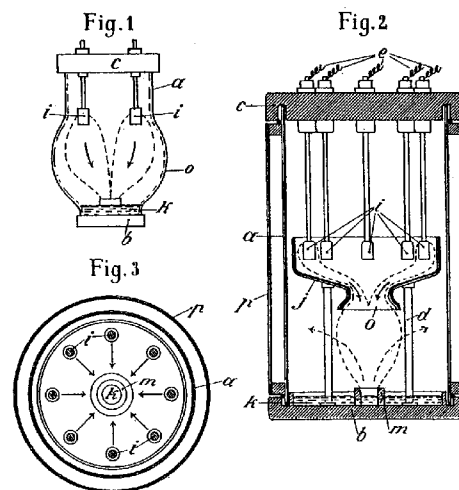
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KLASSE 21g. GRUPPE 12.

EUGEN HARTMANN IN FRANKFURT A. M.-BOCKENHEIM.

Metaldampfgleichrichter mit mehreren von oben hier in das Gefäß eingeführten Anoden.

Patentiert im Deutschen Reiche vom 3. März 1911 ab.



The demand for more powerful rectifier increased quickly, but the possible size of valve found its limits soon. In particular glass had not enough mechanical stability to enlarge valves more and more. The solution was found with a new construction. In 1908 Cooper-Hewitt received a patent for a rectifier with iron vessel. In this way one problem disappeared but a lot of further problems had to be solved, e.g. the ignition of the arc, the sealing of vessel and maintaining vacuum, and the isolation of vessel bushing.

As well engineers in Europe paid attention to rectification. Schott & Gen. a known glass producing Company in Jena and AEG offered the first rectifier with glass bulbs for current between 5 and 30 A used in systems for reloading accumulators or feeding arc lamps. Soon Siemens and BBC (Brown Boveri & Cie) in Switzerland followed.

The development of rectifiers with iron vessel was determined in particular by the Hungarian Bela Schäfer. In 1911 his employer, the company Hartmann & Braun in

Frankfurt, constructed a first rectifier with iron vessel for testing purposes. With it Schäfer formulated basic construction principles (Fig. 8): Several anodes are arranged on a cover plate of the cylindrical iron vessel, which is cooled by water. The mercury cathode in the ground is not isolated from it and the vacuum is maintained with a rotating pump.

In 1911 a first industrial application with two rectifiers for 80 kW had been erected in the foundry Mack in Rödelheim near Frankfurt/M. The application supplied the foundry's DC motors from the public single phase AC city net. One year later an 100 A application at the Straßburg power station for reloading accumulators followed and another year later a 300 kW system at the Maschinenfabrik Lanz in Mannheim.

In 1913 a new actor appeared in Europe: BBC (Brown Boveri & Cie.), in Baden, Switzerland with it's German branch in Mannheim. The company had been established by Charles Brown and Walter Boveri in 1891. Both engineers worked before at the Schweizer Maschinenfabrik Oerlikon and gained experience with electrical power transmissions because Oerlikon – together with AEG – had been involved in construction and erecting the transmission line between the International Exhibition in Frankfurt/M and the generator in Lauffen am Neckar in 1891.

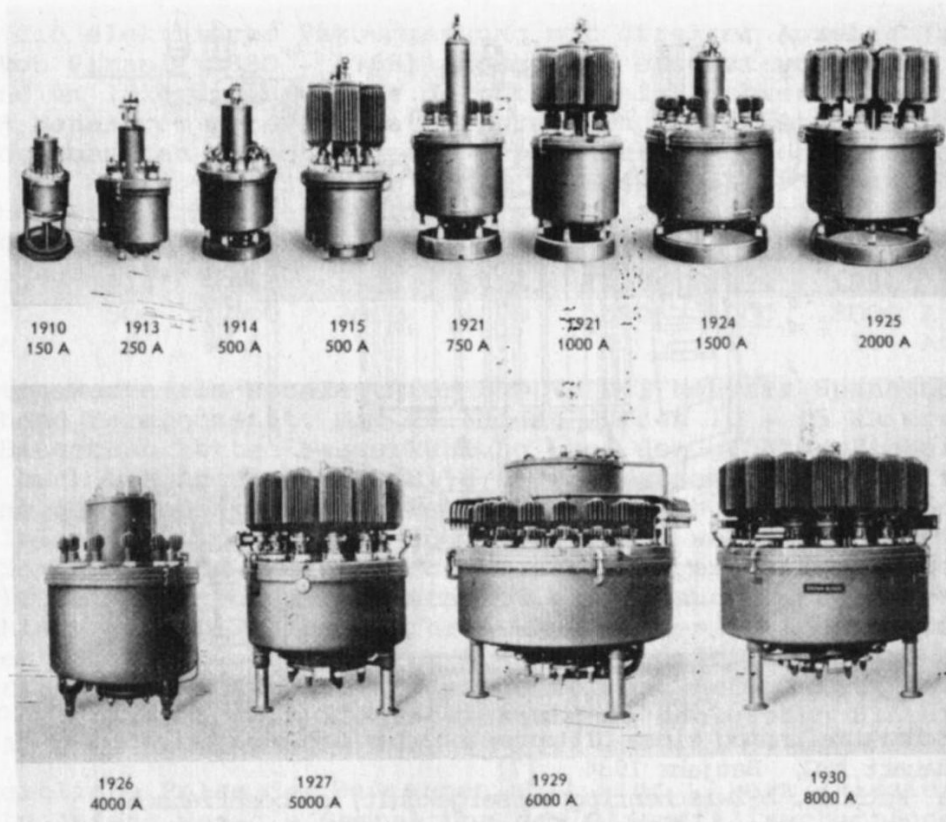


Fig. 9: Development of power rectifiers by Brown Boveri & Cie, Baden, Switzerland, 1910 – 1930 (Anschütz: Geschichte der Stromrichtertechnik mit Quecksilberdampfgefäßen. Berlin et al. 1985; p. 17)

After 1913 BBC developed rectifying technology systematically. The basic shape developed by B. Schäfer had been retained, only the cathode got an isolation from the vessel. The company offered rectifier in two different sizes: 250 A and 500 A. In 1916 a rectification system had been erected at a tram station in Zurich and in 1920 BBC Mannheim built a rectifier station in its own workshop. BBC became a very important company producing static rectifiers which call the company "Mutator". Around that time AEG and Siemens-Schuckertwerke developed rectifier with iron vessel, too. Fig. 9 shows

the development of the BBC rectifiers between 1910 and 1930. Evidently is the tendency to extend the size more and more.

Because of its advantages in the 1920s static rectifiers reached a level to become really a competitor for motor-generators. Important factors are:

- high efficiency, in particular in partial load range,
- less wear because the static rectifiers worked without moving components,
- tolerance of sort-time overload,
- less weight and space
- less noise and vibration,
- easy handling and operation,
- and last but not least the ability of remote control and automated operation.

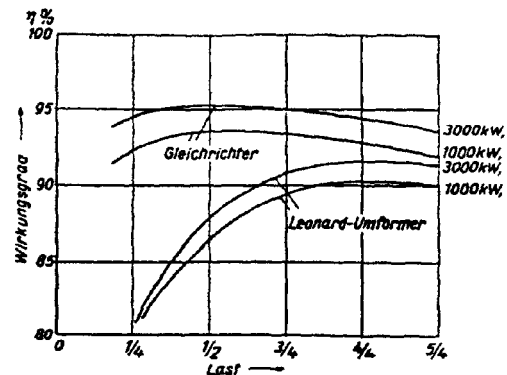


Fig. 10: Efficiency of motor-generator, system Leonard, and static rectifier (AEG Hilfsbuch für elektrische Licht- und Kraftanlagen. 4th ed. Essen 1939; p. 98)

Disadvantages had been the direct transition of load peak into the three-phase power system and the fixed voltages on the secondary DC side, except one used regulating transformers. In contrast the rotary converter, system Leonard allowed an easy change of the DC voltage by regulating generator's excitation and load peaks could be reduce by the rotating mass. On the other side mercury arc rectifiers can work in a wide range of voltages and frequencies, so that one need only a few valve sizes. For less power glass bulb rectifiers were produced. Devices with iron vessel became usual for rectifiers for more power although it needed water for cooling and pumps for vacuum maintenance. However such devices had been robust, short-circuits proof and it was possible to repair it on installation site. In many cases a transformer was necessary for adapting the voltages of the three-phase AC net and the DC system. To decrease the ripple overlaying DC engineers designed special transformers with 6 or even 12 phases.

In very early applications only separate valves had been used. A few years later the situation totally changed. Increasing power could be reached with several anodes, special shaping of arc, better cooling and vacuum maintenance. In the 1920ies only vessels with more than one anode were used. But with this construction the problem of backfire raised what is a reverse current flowing from one anode to another. The valve became very hot and the vessel had been in danger of explosion.

In the case of backfire high current were delivered of both, the transformer at the AC side or a source at the DC side, for example an accumulator. For avoiding damages the current had to be limited with fuses and short-circuit protection.

With intensive research engineers found reasons for backfire and changed the construction, the production process and the operation: First of all the production had to be done under pure conditions what was unusual for mechanical workshops at those time. Additionally all components in the vessel had to be free from internal gas.

3 Grid control

Already in 1902 P. H. Thomas, an assistant of Peter Cooper-Hewitt, suggested to influence DC by phase angle control. However around 10 years later the search for solutions to avoid backfire in multi-anode rectifiers became the starting point for developing grid control. In 1914 the American chemists and physicist Irving Langmuir discovered that the arc ignition can be influenced by an electrode between anode and cathode. A negative grid voltage suppresses an ignition. With the phase angle controlling it was possible to adjust DC from its maximum until zero. In the 1920s grid controlled rectifiers came more and more into practice. Since 1927 negative grid voltage were used to switch off the rectifiers in cases of over load, short-circuit and backfire. Only in the 1930s more applications used grid controlled DC, e.g. in speed controlled drives. At those times providing of appropriate grid signal was a big problem. A sinus voltage often was produced by mechanical contacts.

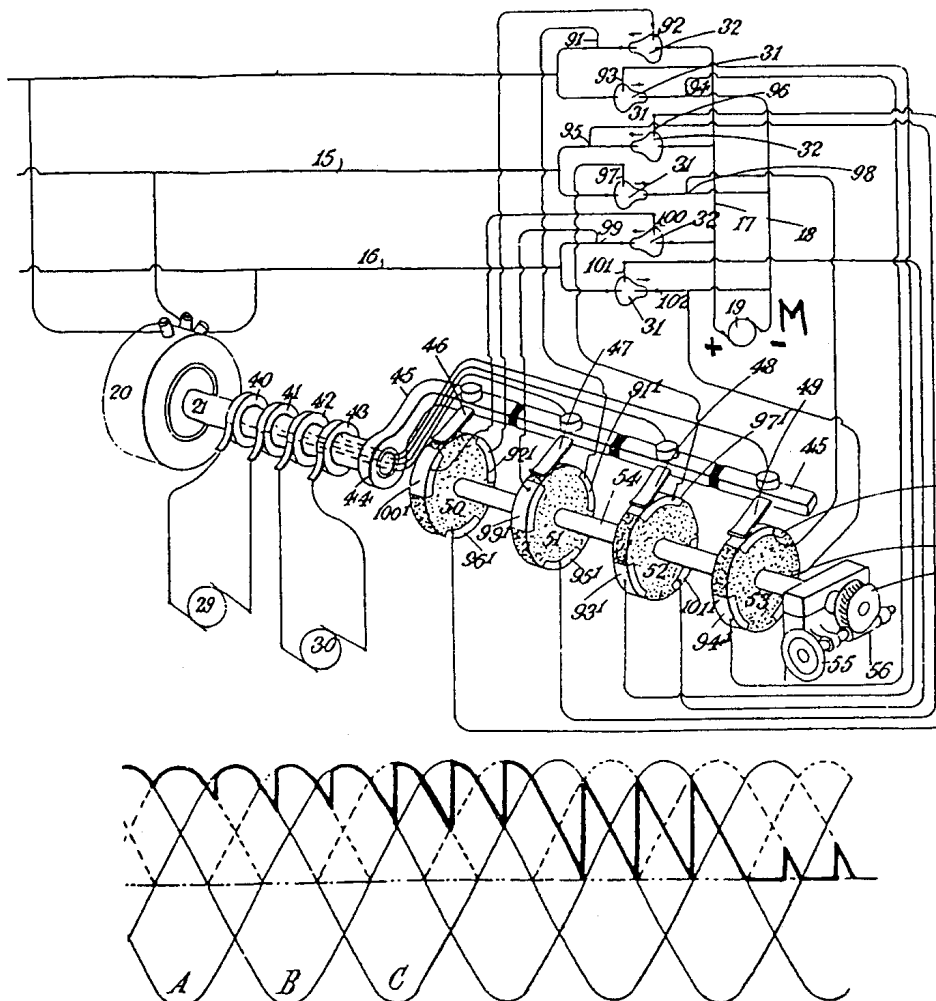


Fig. 11: DC regulation with phase angle controlling, patent by P. H. Thomas 1903
(Kloss: Auf den Spuren der Leistungselektronik. Berlin et al. 1990, p. 145)

Since about 1933 pulses ignition became usual, and after 1935 phase converters, which were circuits for changing the phase shift. Grid controlled mercury arc rectifier made possible a wide field of new opportunities and the engineers dealt with various applications in the 1930s and 1940s.

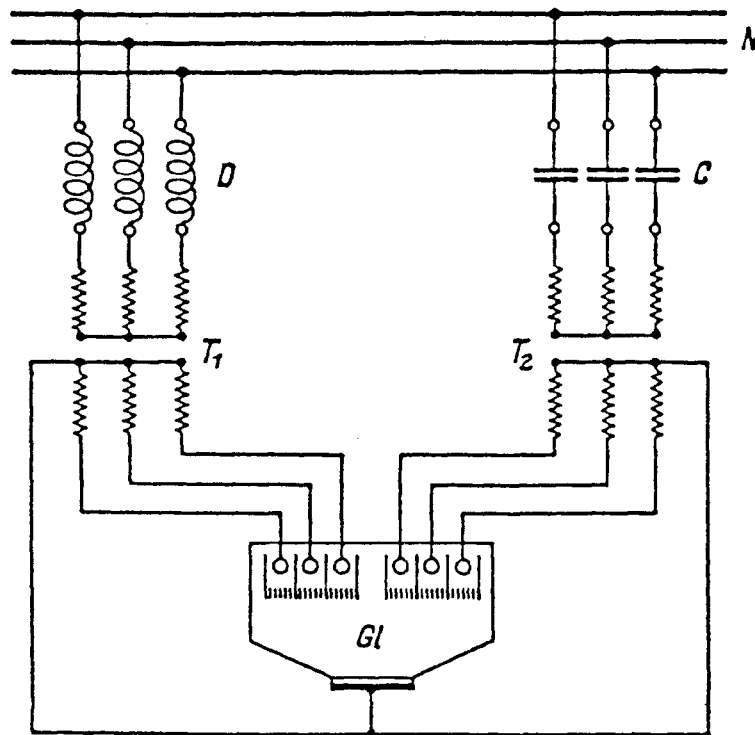


Fig. 12: Application for wattless power compensation by M. Schenkel 1932
(Kloss: Auf den Spuren der Leistungselektronik. Berlin et al. 1990, p. 202)

A serious problem was the backlash on the power supply. The phase-angle control increased the ripple overlaying DC and the power factor on the AC side. Therefore many applications to decrease the reaction on the power supply appeared, that means power factor, shock load and harmonic wave which produces more eddy current and therefore higher losses.

Already in 1892 the German-American engineer Ch. P. Steinmetz discussed the power factor with non-sinus current and analyzed a two phase converter in 1905. In 1912 Krijer, an engineer from the Netherlands, published a paper about power factor of converter with more than one anode. Since those time backlash/reaction remained a difficult part in the construction of power electronic systems until now.

4 Using of Converters

During the 1930s grid controlled valves became more and more usual. In particular in electrolysis for producing chlorine or hydrogen in chemical industry or melting of zinc, aluminum, or magnesium in metallurgical industry. Several power rectifiers in which 12 anodes delivered current of about 80.000 A by voltages of 800 until 1000 V.

An other field of grid controlled valves became the feed of DC power drives, in particular in rolling mills and conveying engines. A first rolling mill had been erected 1936 by Siemens with 6 DC motors and an appropriate converter with 3000 A and 800 V.

In principle static converter can supply DC drives in similar ways like motor generator. Fig. 13 shows a diagram of a reversible drives for a winding tower. The motor can lift on cage I or II by turning clockwise or in opposite (a, b). But the diagram allows also to use the motor

as an electromagnetic brake. The motor becomes a generator and feeds energy back into the power supply (c, d).

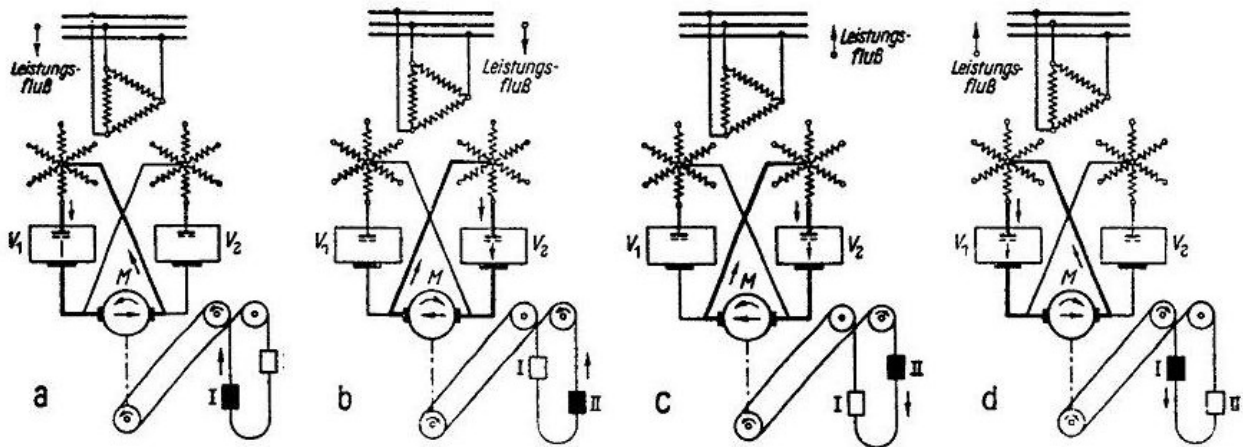


Fig. 13: Reversible drive for winding tower (Hochreuter: Technik und Wirtschaftlichkeit der neuzeitlichen elektrischen Fördermaschine, in: Elektrotechnik u. Maschinenbau 60, 1942, No. 7/8, pp. 65-79, p. 73)

However DC reversible drives found acceptance only slowly, on one hand because of technical difficulties and on the other hand because of the big wattful and blind current stressing the three-phase AC power network .

5 AC-AC converter

Furthermore in the 1930s AC-AC frequency converters were designed and tested under real conditions. Such a converter is formed by coupling a rectifier and an inverter connected by a DC intermediate circuit. This allows to construct adjustable-speed drives with three phase induction motors. The speed can be changed easily by variation of frequency.

AC-AC converter had been used particularly in power supply for electric traction systems (Fig. 14). The standard railway in some European countries operates with single-phase AC with frequency of $16 \frac{2}{3}$ Hz. In most of the cases public networks delivered electricity by using a motor generator. Because of the better efficiency in 1930s the Deutsche Reichsbahn company wished to use more static converters. Already in the 1931 an AC-AC converter of 100 kW had been tested by the Deutsche Reichsbahn. One year later the Siemens Company erected an AC-AC converter for elastic coupling of a 110 kV 3-phase AC net with 50 Hz and a $16 \frac{2}{3}$ Hz electric railway network. However the system was not successful. Because of bad power factor and many problems with the control system the converter operated only 2 years. In 1938 BBC erected in Pforzheim a 3 MW power supply the 110 KV railway network.

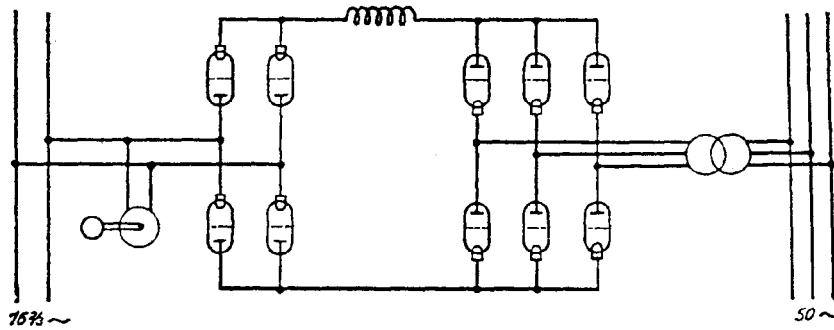


Fig. 14: AC-AC frequency converter with DC circuit by AEG 1932
(Kloss: Auf den Spuren der Leistungselektronik. Berlin et al. 1990, p. 202)

Another application field of great importance is High Voltage DC power transmission. There the DC intermediate circuit works with very high voltage and rectifier and inverter are separated by long distance. Such systems can transmit electricity over long distances and only need two conductors which save a lot of money by erecting the system. In Germany this field of application received a strong support because of the hope this technology could help to transmit electricity from occupied countries with water power, like Scandinavia or Austria, into the Reich.

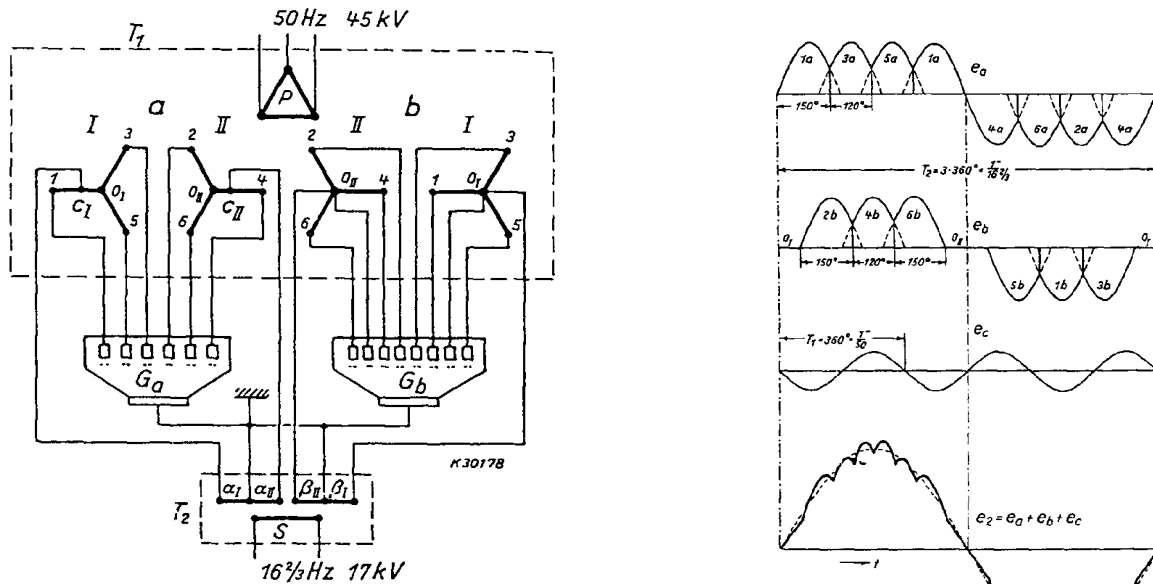


Fig. 15: Envelope curve AC-AC converter by AEG 1936 (Kloss: Auf den Spuren der Leistungselektronik. Berlin et al. 1990, p. 203)

After experimenting with some smaller systems, in 1935 AEG erected a pilot plant in Henningsdorf near Berlin using special high pressure valves system Erwin Marx. Because the material problems could not be solved later only mercury arc rectifies had been used. BBC operated around 1940 with a 25 km experimental transmission line with 50 kV and 30 A between Wettingen and Zurich. Between 1942 and 1944 Siemens operated with a 15-MW/100-kV-transmission between Charlottenburg and Moabit in Berlin about 5 km. At the end of the World War II AEG and Siemens erected 60-MW-power transmission with plus

and minus 200 kV, together 400 kV, between Dessau and Berlin, finished in 1945. Special troops of the Soviet Red Army troops dismantled it totally and Soviet engineers used the equipment for erecting transmission line between Kaschira and Moscow with 200 kV, 30 MW over a distance of 112 km in 1950. After World War II several High Voltage DC transmissions had been built. Because of its DC circuit HVDC systems can not transmit wattless power. Therefore DC coupling is suitable for connecting different networks to avoid that a collapse in one network can spread out on the other.

In opposite to converter with DC intermediate circuit it is also possible to connect two inverters in different ways. In an envelope curve converter (Fig. 15) the voltages of two converters are added in a way that in the result an secondary voltage with a changed frequency appears. Beside that direct converters had been developed which deliver a saw-toothed voltage shaping by a transformer into a secondary voltage with lower frequency (Fig. 16). However direct inverters have a bad power factor and produces a lot of wattless power. Additionally a sophisticated device for control the inverter is necessary. Such direct converters in particular were used for elastic coupling of different networks which is able to transmit wattless power, too.

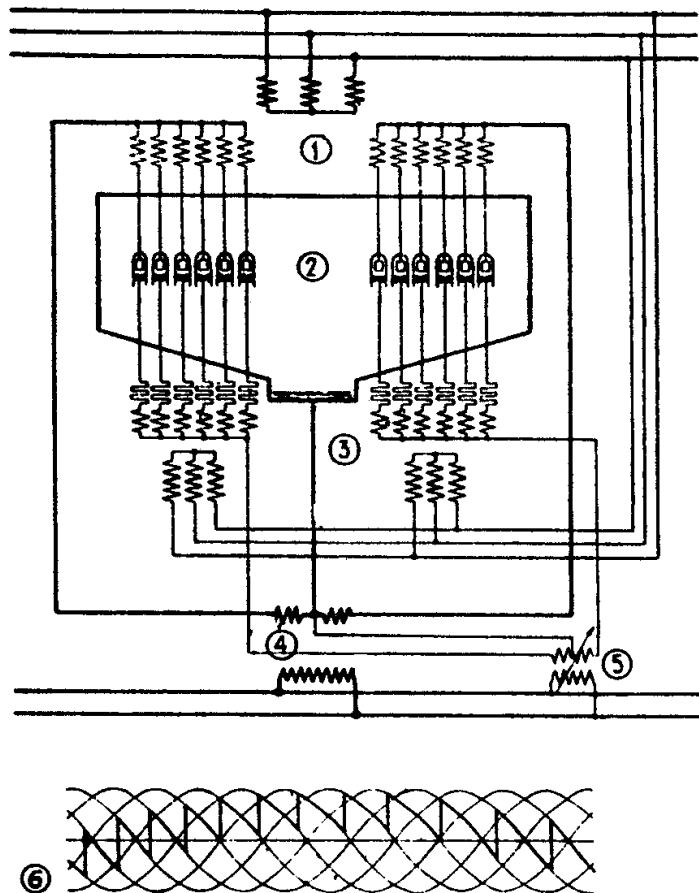


Fig. 16: Direct AC-AC converter by Siemens-Schuckertwerke 1933 (Wechmann: Bahnstrom aus der öffentlichen Elektrizitätsversorgung unter Berücksichtigung der neuesten Technik, in: Transactions of the World Power Conference, Sectional Meeting Scandinavia 1933; Vol VI, Stockholm, 1934; pp. 111-121, p. 118)

Because of the many problems engineers tried to feed locomotives directly with 50 Hz electricity. A few experiences occurred already in 1928 when 5 experimental locomotives operated at the main station in Munich. In 1936 the Deutsche Reichsbahn bought 4 experimental locomotives with 20 kV power and 50 Hz for testing operation on a very

steep 30 km long railway line The AEG locomotive used a mercury arc rectifier with grid control for voltage adjustancy and the locomotive of BBC used the same component for switching off the converter in cases of any errors.

Because AC converters react very quickly and without sparks at the beginning of the 1930 the idea raised to use it to replace mechanical commutators of DC motors (Fig. 17). But this idea first could be realized for industrial purposes in the 1950s with solid state devices.

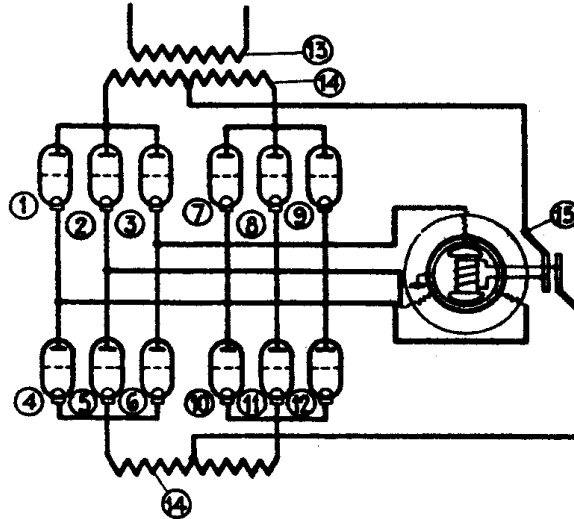


Fig. 17: Converter fed motor without commutator by AEG 1933 (Wechmann: Bahnstrom aus der öffentlichen Elektrizitätsversorgung unter Berücksichtigung der neuesten Technik, in: Transactions of the World Power Conference, Sectional Meeting Scandinavia 1933; Vol VI, Stockholm, 1934; pp. 111-121, p. 118)

6 Conclusion

Parallel and following the described development of power electronics with mercury power valves many other remarkable aspects had to be mentioned, There are for example the competitors of mercury arc rectifiers like gas filled tubes, magnetic amplifiers called transductor, and solid-state devices, e.g. classic thyristors, triacs, GTO [Gate turn off]-thyristors, different types of power transistors, and smart power IC's. However this is an other story and can not be considered in this paper.

In conclusion the history of power electronics can be summarized as the struggle of engineers of both, to improve the quality of adapting power supply and load, and to decrease the losses in the process. The last effort corresponds with an idea of Wilhelm Ostwald, Nobel Prize winner of chemistry in 1909. Ostwald formed the so called "energetic imperative" described shortly with the motto: "Don't waste energy, use it."

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