Solidifying Power Electronics [Historical]

Publisher:
Institute of Electrical and Electronics Engineers Inc.

Published version:
DOI: 10.1109/MIE.2018.2791062

Solidifying Power Electronics

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More than a century ago, in 1902, American Engineer Peter Cooper Hewitt (1861–1921) derived the mercury-arc rectifier, enclosed in a glass bulb, from his mercury-vapor lamp of the previous year. He devised its use for feeding dc motors from alternating currents. As the first rectifier for power uses (two years before John Ambrose Fleming's diode and four years before Lee de Forest's audion [1]), the mercury-arc rectifier marked the birth of power electronics. The device was used in 1905 in Schenectady, New York, for powering a dc line for incandescent lamps and, soon after, in rectifiers for battery chargers and electrochemical processes, including aluminum reduction and electroplating. Aiming for higher powers, Cooper Hewitt introduced the metal casing with water cooling in 1909.

In the same year, the Hungarian engineer Béla B. Schäfer (1879–?), of the German company Hartmann & Braun (H&B), applied for his first patent on mercury-arc rectifiers, which were first delivered to a German foundry in 1911. After an agreement between H&B and the Swiss-owned Brown Boveri Company, high-power models (300 kW at 600 V) with a metal casing were produced in 1913 [2]. Steel-tank rectifiers could carry 750-A currents by 1915, and General Electric (GE) started producing similar devices in 1919; Siemens–Schuckert introduced a water-cooled model in 1920. Westinghouse and Allgemeine Elektricitäts–Gesellschaft (AEG) also entered the market in the 1920s, while the devices' ratings gradually increased [3].

FIGURE 1 – A large GE thyratron (used in pulsed radars) next to a miniature 2D21 thyratron (used to control relays). (Courtesy of Wikimedia Commons.)

Early studies on controlled rectification in gas tubes were developed at GE by Irving Langmuir (1881–1957) and his colleagues in 1914, when they discovered that a negative potential introduced between a cathode and an anode by a third electrode prevented the anode current. High-power mercury-arc controlled valves, i.e., switches, were developed in the 1920s and 1930s, providing significant improvements to electric railway converter stations and electrochemical plants. The idea of using grid control in combination with phase retard to modulate ac power had emerged in the early 1920s, and, by 1925, the name *inverter* was introduced. Fundamental converter topologies appeared during those two decades. New York City's underground was dc fed through 3-MW mercury-vapor rectifiers in 1930, and German railways adopted mercury-arc cycloconverters for a universal motor drive in 1931. Such power grid applications called for devices capable of higher voltages.

By 1932, AEG was producing high-power (750 kW at 3 kV) mercury-vapor rectifiers provided with a glass casing (Figure 1). GE used similar devices in the 12-kV dc transmission line connecting a 40-Hz power station to 60-Hz loads at Mechanicville, New York, in 1932 [4]. The device, known as an *ignitron*, is a high-current, high-voltage (HV) mercury-vapor controlled rectifier developed by Joseph Slepian (1891–1969) at Westinghouse in 1931. It has a water-cooled steel casing for withstanding high currents between a cathode and an anode, started by a triggering pulse in the third electrode, and was used in topologies such as an inverse parallel for ac control in welding and heating and in bridge rectifiers for supplying railways and mills. Recently, it has been replaced by semiconductor switches, but it is still used in some high-power pulsed applications because of its robustness.

The device, known as a *thyratron,* was first used close to 1928 [5]. It was a hot-cathode mercury-arc controlled valve that was developed by building on the argon-filled vacuum tubes used in radio detectors. It featured an anode, a heated cathode, and a grid acting as the control electrode that could start an anode-to-cathode positive current and was enclosed in a glass casing filled with mercury vapor to provide low direct voltage. It became popular for a number of low-power applications. Uncontrolled diode versions, known as *phanotrons*, were also produced. The first variable-frequency ac drive of a synchronous motor was developed by Ernst Alexanderson (1878–1975) at GE Corporate Research and Development (GE-CRD) in 1934 using thyratrons [6]. These devices are still used for some high-power (tens of kiloamps and tens of kilovolts) pulsed operation systems, e.g., lasers, radiotherapy devices, and crowbar circuits of TV broadcasting stations.

After Schäfer sold his know-how to Allmanna Svenka Elektriska Aktiebolaget [(ASEA), now ABB after merging with the Brown Boveri Company in 1998] in 1927, an advanced HV mercury-arc valve was made possible by the grading electrode design invented by Uno Lamm (1904–1989) of ASEA in 1929. It allowed HVdc lines operating at hundreds of kilovolts to be put into service in subsequent decades. Multianode devices for multiphase operations, with both steel and glass casings, were available in the late 1930s (Figure 2).

Early power solid-state rectifiers appeared during this era. Grondahl [7] and his coworkers at Union Switch and Signal Company had studied the conduction between copper and copper oxide since 1920, establishing the basis of metallic rectifiers. They obtained early practical devices four years later and patented the solid-oxide rectifier in 1927. Thanks to planar geometry, it could withstand relatively high currents (i.e., 7 A, much higher than the solid-state galena contact point rectifier introduced by Karl F. Braun in 1874 and developed some years later in the galena cat's-whisker detectors [8]) with current densities up to 310 mA/cm^2 without a heat sink and limited direct/inverse voltages (i.e., lower than 6 V). However, by 1948, copper-oxide rectifiers had grown considerably. Assembled in series and in parallel, they could cover a wide range of different applications with currents up to 25–100 kA (rectifiers for plating) and voltages up to 1,500 kV (atomic physics experiments) [9]. Building on early observations by Braun, William G. Adams, and others in 1874–1876, Ernst Presser at TeKaDe, Germany, developed the selenium rectifier in 1928. It consisted of a layer of selenium applied to an aluminum plate. Despite operating at a current density lower than the copper-oxide rectifier, it was the first solid-state metal diode suitable for more general power uses, by virtue of rated voltages of up to 30 V.

In the 1940s, power electronics dealt with the conversion of electric power from ac to dc (or vice versa) in dc power transmission, with the conversion from one frequency to the other in operating ac motors at variable speed and with transforming high ac voltage to low ac voltage [10].

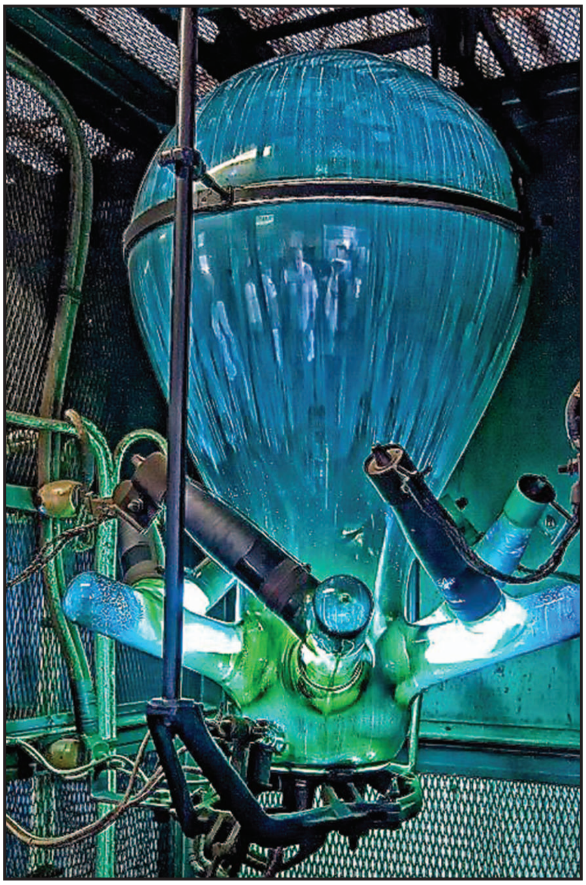

FIGURE 2 – A multianode mercury-arc rectifier still in operation in October 2010 at Manx Electric Railway substation at the Laxey Isle of Man. (Image courtesy of Tony S. at Talk Electrician Forum.)

The invention of the point-contact transistor at Bell Labs by John Bardeen and Walter H. Brattain in late 1947, and the junction transistor by William B. Shockley in early 1948 [11], opened the door to a completely new generation of power devices, starting with a controlled semiconductor rectifier. After joining Bell Labs in 1951, Jewell James Ebers (1921–1959) developed a model of a p-n-p-n device as the combination of a p-n-p and an n-p-n transistor. This had to be developed as a three-electrode solid-state device made with four layers of alternating p- and n-type semiconductors. Analyses showed that it could act as a bistable switch conducting between an anode and cathode when the gate received a trigger current and continued to conduct while the voltage across the device was not reversed (forward biased) [12].

Shockley later claimed he originated the device by reason of the hook collector, i.e., the negative resistance effect that he interpreted for the transistor, which also appeared in the p-n-p-n switch. The construction of the p-n-p-n switch was undertaken by a Bell Labs group led by John L. Moll (1921–2011), who argued in favor of using silicon technology to make the device instead of germanium, as was customary in the transistors of the day. The first silicon transistor was made by Morris Tanenbaum (b. 1928) at Bell Labs in January 1954. After Moll's group had been reinforced by James M. Goldey (b. 1926) and Nick Holonyak (b. 1928), prototypes of the p-n-p-n switch were built by Tanenbaum, Goldey, and Holonyak in 1954–1955, all based on silicon.

Bell Labs did not arrive at an industrialized design; rather, the GE rectifier department under the supervision of R.A. York started a program in 1957 to build a silicon-controlled rectifier (SCR) that was actually a three-terminal p-n-p-n switch [13]. Starting with a crude technology, York's group was able to produce a kilowatt-level (i.e., hundreds of volts and tens of amperes) prototype by July 1957. Later the same year, Holonyak joined the GE group and worked on improving the device. Thanks to the efforts of Frank W. "Bill" Gutzwiller (c.1926–2011), it was successfully marketed in early 1958, thus starting a revolution in power electronics (Figure 3). *Thyristor*, the name for the p-n-p-n switch, was coined in 1966 by merging thyratron and transistor, since it was intended to be a competitor of the former.

FIGURE 3 – An early thryristor. (Courtesy of ABB Company.)

Silicon technology, specifically conceived for thyristors, later played a fundamental role in the development of electronics. Its use became common in other solid-state devices and chips, starting with silicon-wafer processing to make p–n-junction devices by impurity diffusion. Shockley, despite resigning from Bell Labs in 1953, had access to this new silicon technology and took it with him when he moved to California, in an area now known as *Silicon Valley*. He made the information on the silicon p-n-p-n available to his recruits at Shockley Semiconductor Laboratory, established in 1956 in Mountain View (with Robert Noyce and Gordon Moore), who could take the silicon technology in a different direction [14]. Other power devices, including power diodes based on either silicon or germanium, were produced in the mid-1950s and started replacing mercury-arc valves. Another early device for power uses was the planar-type Darlington bipolar power transistor (BPT), a device invented by Bell Labs Engineer Sidney Darlington (1906–1997) in 1953 by combining two (or three) bipolar junction transistors (BJTs) that share a common collector [15]. Westinghouse announced a solid-state controlled rectifier called a *trinistor* in July 1959. By the 1960s, the improved switching speed of BJTs ushered in BPTs suitable for high-frequency dc/dc converters, a pivotal innovation in power electronics that was marketed in the late 1970s.

In 1958, GE Engineers York and Holonyak developed the SCR concept into a symmetrical switch, building on the shorted-emitter idea. The device they created operated properly and reliably, and it became the prototype of the triode for alternating current (TRIAC), a device capable of conducting currents of either sign when triggered. However, it suffered from turn-off failures when used with reactive loads and from turn-on failures after HV derivatives, which called for snubber circuits. In the case of demanding circuits, two inversely paralleled SCRs were preferred. Holonyak was the only researcher who participated in the first Bell Labs studies as well as the early GE work on p-n-p-n switches (SCR and TRIAC), and he did not limit his contributions to power devices. He built the first real light-emitting diode capable of emitting visible light and the red-light (visible) semiconductor laser, both in 1962 [16].

FIGURE 4 – A family of GTOs of different sizes from ABB, rated up to 4.5 kV and 4 kA. (Courtesy of ABB Company.)

In the 1970s, the evolution of electronic converters called for devices capable of self-turn-off, fast-switching, and high-withstand capability; they were achieved by building upon SCR technology [17]. A solution was found in the gate turn-off (GTO) thyristor. Invented in GE's laboratories in 1958 and made available in 1962, it was a switch similar to the TRIAC but was fully controllable since it could be turned off at will by ceasing the gate signal. However, GTOs required powerful driving circuits capable of quickly extracting high-reverse currents form the device gate and external snubber circuits to shape the turn-on and turn-off currents to protect the device against destructive commutations. Both devices presented a beneficial, low forward voltage. GTOs, produced in high-rating models by Japanese companies, and BPTs, both marketed in the late 1970s, were the main devices for medium- and high-power electronics applications in the early 1980s (Figure 4).

Another switch that appeared during this period was the power metal–oxide–semiconductor field-effect transistor (MOSFET), which became commercially available in 1976 and found preferential use in the lower voltage applications (e.g., switching-mode power supplies) because of the negligible control power required by the MOS gate structure and of the fast-switching characteristics. The latter feature was crucial in coping with increased carrier frequency necessitated by the development of pulse-width modulation (PWM) control, but it also exhibited poor power handling capabilities at higher breakdown voltage, compared with the BPT. Power MOSFETs are still popular for low-voltage, high-frequency applications.

Thyristor- and transistor-based devices dominated power electronics from the 1960s to the 1980s. They evolved into a strong alternative to the thyratron, drove the development of electric power converters, and became the workhorse of the power industry. Their superior switching and control allowed advanced topologies to be introduced that were capable of addressing poor power factor and high harmonics issues. William McMurray (1926–2006) of GE-CRD proposed forced-commutation converter topologies in 1961. After SCR-based, variable-voltage constant-frequency drives for induction motors were proposed in 1964, the McMurray inverter and the McMurray–Bedford inverter were essential to the introduction of variable-frequency drives, which expanded the operability of the induction motor and provided rated torque at any speed.

Used in suitable converter topologies, e.g., a six-pulse Graetz bridge, SCRs were at the basis of second-generation HVdc technology. By 1979, top-performing 3.2-kV SCRs were developed by AEG in Germany under GE's license for the 1.9-GW ±533-kV conversion stations of the Cabora Bassa–Johannesburg HVdc line, superseding ASEA's dominant mercury-valve technology [4]. During this period, PWM was introduced in ac motor control. Though switching devices were not yet commercially available, in 1976, Gyugyi and Pelly presented a comprehensive analysis of switching converters in various applications [18] that envisioned the future of PWM-driven converters.

THYRISTOR- AND TRANSISTOR-BASED DEVICES DOMINATED POWER ELECTRONICS FROM THE 1960s TO THE 1980s.

To impact higher voltage systems, a new class of power devices based on a combination of bipolar and MOS physics was needed. The concept of a composite device was introduced for the first time by Yamagami et al. in a Japanese patent regarding a wide base p-n-p transistor driven by an n-MOSFET in 1968 [19]. Subsequent discoveries led to the development of the insulated-gate bipolar transistor (IGBT), consisting of four alternating p-n-p-n layers controlled by a MOS gate structure that resulted in a high-current power transistor with null consumption at the control electrode. Early successful experiments were reported by J.D. Plummer and B.W. Schaft in 1978 and, independently, by Indian-born, American engineer Baliga [20] (b. 1948) in 1979.

Improvements came in the following years. Nakagawa et al. proposed the non-latch-up structure, marking the birth of the practical IGBT in 1984 [21]. Its design and fabrication process technologies were derived from the power MOSFET, with much effort made to implement trench technology. With important contributions from numerical simulations, more improvements to IGBTs came in the following years. This work led to an IGBT that, unlike GTOs, does not require snubber circuits or complex driving circuits. Although early devices were marketed in 1982, successful commercial models didn't appear until 1984. IGBTs are now the most important devices for medium-to-high power applications and are widely used in motor drives, uninterruptible power supply, and renewable energy sources.

Beginning in the 1980s, ABB and Mitsubishi collaborated to develop the integrated gate-commutated thyristor (IGCT) to provide more superior performance than that of the BPT, which suffered from low current gain when designed for HVs and required snubber circuits. The IGCT, introduced in 1997 as a competitor of the IGBT, combines a MOSFET operation and a bipolar transistor that allows it to be switched on and off by the control electrode and results in a compact, low-cost gate drive circuit and low-forward voltage. The first generation of the emitter turn-off (ETO) thyristor was developed by the Center for Power Electronics, Virginia Tech University, in 1999. This composite device consists of a thyristor that uses a MOSFET to turn on and turn off and has two gates: one normal gate for turn on and one with a series MOSFET for turn off. In this way, it merges the benefits of both the GTO and MOSFET with clear advantages with respect to the IGCT. As of 2016, ratings as high as 8.5 kV/5 kA for SCRs, 6.5 kV/3.8 kA for IGCTs, 6.5 kV/0.75 kA for IGBTs, and 4.5 kV/4 kA for ETOs have been achieved [22].

If, on one hand, each generation of devices addressed the development of power electronic controllers and their applications, the history of power electronics, on the other hand, has not been as straightforward. Several power devices, typically derived from transistors and thyristors, were proposed in the 1970s and 1980s, but most were not successful. This was the case with the static induction thyristor, the static induction transistor, and the MOS-controlled thyristor, despite intense research efforts and costs. Nevertheless, the general advancement has been of paramount importance. Self-commutated devices (e.g., power MOSFETs, BPTs, GTOs, IGBTs, and IGCTs) have largely replaced SCRs and allowed the introduction of advanced topologies, which, together with advanced control techniques, resulted in power converters with superior performance. Notable examples are the popular voltage-fed converter, the hysteresis-band sinusoidal current control (1979), and the matrix converter, invented by Marco Venturini in 1980 and based on inverse-parallel ac switches. The neutral-point clamper multilevel converter, also introduced in 1980, is now very popular. Modular multilevel converters and step-wave approximations have mainly been used from the 1990s to 2010.

Notable developments were the PWM-selected harmonic elimination invented by Fred Turnbull at GE-CRD in 1963 and perfected by Patel and Hoft (1973), the sinusoidal PWM technique of Schonung and Stemmler (1964), and the space vector PWM technique (1982) perfected by Lipo (1995). With regard to motor drives, vector controls were introduced in the late 1960s (Hasse, 1969) and early 1970s (Blaschke, 1972), and direct torque control, an advanced scalar control technique, was presented by Manfred Depenbrock in Germany (1984) and by Isao Takahashi in Japan (1985). In smart and flexible ac grids, static synchronous series compensators allow for fast control of equivalent capacitance or inductance, and thyristor-controlled series capacitors provide fast capacitive reactance adjustment in volt–ampere reactive and harmonic compensators as well as improved load performance. Power electronics has found other major applications in electrochemical processes, heating and lighting control, electronic welding, industrial automation, and high-frequency heating. Power electronic systems have largely benefitted from the use of digital microelectronics in their control circuits, including microcomputers/digital signal processors and application-specified integrated circuit/field-programmable gate array chips.

The success of solid-state power devices allowed power electronics to steadily progress over the years, with more workers working on power electronics projects. By the early 1980s, power electronics achieved recognition as a technology in its own right. The Council of Power Electronics was established in 1983 to advance and coordinate work in the field carried out through the IEEE. Today, a substantial number of devices employing power electronics are present in our factories, offices, and homes. In the future, power electronics devices are expected to change power grids and influence technologies, e.g., ultra-HVdc (UHVdc). Extended dc grids, flexible ac transmission systems, and flexible substations will become a significant technological field of development. UHVdc is expected to reach ratings of 1,100 kV and 20 GW on extensions of 3,000 km. For decarbonization programs, power electronics is closely involved with renewable energy systems, photovoltaic and fuel cell power conversion, energy storage, battery management, electric and hybrid vehicles, smart grids, and microgrids. Power electronics has emerged as a high-tech frontier in power engineering, promising to evolve into future devices with superior performance based on the use of large-bandgap materials.

Acknowledgment

I wish to thank Paolo Tenti of the University of Padova, Italy, for his valuable assistance with writing this column.

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