Power Electronics—Historical Perspective and **My Experience**

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Power electronics is a technology that deals with the conversion and control of electrical power with high-efficiency switching mode electronic devices for applications such as dc and ac power supplies, electrochemical processes, heating and lighting control, electronic welding, power line volt–ampere reactive (VAR) and harmonic compensators, high-voltage dc (HVdc) systems, flexible ac transmission systems, photovoltaic and fuel cell power conversion, high-frequency (HF) heating, and motor drives. We can define the 21st century as the golden age of power electronics applications after the technology evolution stabilized in the latter part of the past century with major innovations.

Power electronics is ushering in a new kind of industrial revolution because of its important role in energy conservation, renewable energy systems, bulk utility energy storage, and electric and hybrid vehicles, in addition to its traditional roles in industrial automation and high-efficiency energy systems. It has emerged as the high-tech frontier in power engineering. From current trends, it is evident that power electronics will play a significant role in solving our climate change (or global warming) problems, which are so important.

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Power electronics has recently emerged as a complex and multidisciplinary technology after the last several decades of technology evolution made possible by the relentless efforts of so many university scientists and engineers in the industry. The technology embraces the areas of power semiconductor devices, converter circuits, electrical machines, drives, advanced control techniques, computer-aided design and simulation, digital signal processors (DSPs) and field-programmable gate arrays (FPGAs), as well as artificial intelligence (AI) techniques.

The history of power electronics is so vast that it is impossible to review it within a few pages. I will attempt to give a brief overview of the historical perspective, highlighting the salient inventions and occasionally inserting my own experience and comments. Information is also available from the references.

Power Electronics in the Classical Era

The history of power electronics goes back more than 100 years. It began at the dawn of the 20th century with the invention of the mercury-arc rectifier [1] by the American inventor Peter Cooper Hewitt, beginning what is called the "classical era" of power electronics. However, even before the classical era started, many power conversion and control functions were possible using rotating electrical machines, which have a longer history.

Electrical Machines

The advent of electrical machines [2] in the 19th century and the commercial availability of electrical power around the same time began the so-called electrical revolution. This followed the industrial revolution in the 18th century, The commercial wound-rotor induction motor (WRIM) was invented by Nikola Tesla in 1888 using the rotating magnetic field with polyphase stator winding that was invented by Italian scientist Galileo Ferraris in 1885. The cage-type induction motor (IM) was invented by German engineer Mikhail Debrovolsky in 1889. The history of dc and synchronous machines is older. Although Michael Faraday introduced the dc disk generator (1831), a dc motor was patented by the American inventor Thomas Davenport (1837) and was commercially used from 1892. Polyphase alternators were commercially available around 1891. The concept of a switched reluctance machine (SRM) was known in Europe in the early 1830s, but as it was an electronic machine, the idea did not go far until the advent of self-commutated devices in the 1980s. The duality of the motoring and generating functions of a machine was well known after its invention. The commercial dc and ac power generation

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and distribution were promoted after the invention of machines. For example, dc distribution was set up in New York City in 1882 mainly for street car dc motor drives and incandescent carbon filament lamps (1879) developed by Thomas Edison. However, ac transmission at a higher voltage and longer distance was promoted by Tesla and was first erected between Buffalo and New York (1886). Those were the exciting days in the history of the electrical revolution. (See "Edison Versus Tesla.")

Although rotating machines could be used for power conversion in the prepower electronics era (the late 19th century), they were heavy, noisy, and the efficiency was poor. A dc generator coupled to a synchronous motor (SM) or an IM could convert ac to dc power, where dc voltage could be varied by controlling the generator field current. Similarly, a dc motor could be coupled to an alternator to convert dc to ac power, where the output frequency and voltage could be varied by motor speed variation with field current and alternator dc excitation, respectively. The ac–ac power conversion at a constant frequency and variable voltage was possible by coupling an alternator with an IM or an SM, where the alternator dc excitation was varied. Generating the variable-frequency supply required for ac motor speed control was not easy in the early days.

How could you control the speed of the dc and ac motors that were so important for the processing industries? Controlling the speed of a dc motor was somewhat straightforward and was done by varying the supply voltage and motor field current. However, ac motors were generally used for constant-speed applications. The historic Ward-Leonard method of dc motor speed control was introduced in 1891 for industrial applications. In this scheme, the variable dc voltage for the motor was generated by an IM dc generator set by controlling the generator field current. In the constant-torque region, the dc voltage was controlled at a constant motor field current, whereas the motor field current was weakened at higher speed in the constant-power region. The four-quadrant speed control was easily possible by reversing the dc supply voltage and motor field current. The speed control of the ac motor was more difficult without the help of power electronics.

For a WRIM, the rotor winding terminals could be brought out by the slip rings and brushes, and an external rheostat could control the speed, although efficiency is very poor in such a scheme. Changing the number of stator poles is the simple principle for ac motor speed control, but the complexity and discrete steps of speed control could not favor this scheme. German inventors introduced two methods of WRIM speed control with slip energy recovery by the cascaded connection of machines, which are known as the Kramer drive (1906) and the Scherbius drive (1907). In the former method, the slip energy (at slip frequency) drives a rotary converter that converts ac to dc and drives a dc motor mounted on the WRIM shaft. The feedback of the slip energy on the drive shaft improves the system efficiency. In the Scherbius drive, the slip energy drives an ac commutator motor, and an alternator coupled to its shaft recovers the slip energy and feeds back to the supply mains. Both systems were very expensive. Both the Kramer and Scherbius drives are extensively used today, but the auxiliary machines are replaced by power electronics. For completeness, the Schrage motor drive (1914) invented in Germany, which replaces all the auxiliary machines at the cost of complexity of motor construction, should be mentioned. It is basically an inside-out WRIM with an auxiliary rotor winding with commutators and brushes that inject voltage on the secondary stator winding to control the motor speed. (See "My Undergraduate Days.")

Mercury-Arc Rectifiers

The history of power electronics began with the invention of the glass-bulb pool-cathode mercury-arc rectifier [1] by the American inventor Peter Cooper Hewitt in 1902. While experimenting with the mercury vapor lamp, which he patented in 1901, he found that current flows in one direction only, from anode to cathode, thus giving rectifying action. Multianode tubes with a single pool cathode could be built to provide single and multiphase half-wave diode rectifier operation with the appropriate connection of transformers on the ac side. The limited amount of dc voltage control was possible by tap-changing transformers. The rectifiers found immediate applications in battery charging and electrochemical processes such as Al reduction, electroplating, and chemical gas production. The first dc distribution line (1905) with the mercury-arc rectifiers was constructed in Schenectady, New York, and used for lighting incandescent lamps. Hewitt later modified glass bulbs with steel tanks (1909) for higher power and improved reliability with water cooling that further promoted the rectifier applications. The introduction of grid control by Langmuir (1914) in mercury-arc rectifiers ushered in a

EDISON VERSUS TESLA

Thomas Edison (1847–1931) and Nikola Tesla (1856–1943) were the inventing wizards of the 19th (and also the 20th) century, and their contributions significantly influenced the history of electrical engineering. Edison described genius as "99% perspiration and 1% inspiration." He had 1,093 U.S. patents even though he did not complete his high school education. Tesla came to the United States from Serbia (now Croatia) to work with Edison, but they developed a hostile relationship. Edison was a proponent of dc power because, according to him, ac was too dangerous for human beings. Tesla, on the other hand, was a proponent of ac power. This is historically known as the "war of currents." History eventually showed the superiority of ac power for generation and long-distance transmission with the help of transformers. However, dc power proved superior for long-distance transmission through HVdc. DC distribution is now being seriously considered for low-voltage, low-power renewable energy systems. Edison and Tesla were rumored to have shared the Nobel Prize in Physics, but this was not true.

new era that further boosted their applications. The rectifier circuit could also be operated as a line-commutated inverter by retarding the firing angle. Most of the phase-controlled thyristor converter circuits used today were born in this classical era of power electronics evolution. It is interesting to note that, in 1930, the New York City subway installed a 3,000-kW grid-controlled rectifier for traction dc motor drives. In 1931, German railways introduced mercury-arc cycloconverters (CCVs) that converted three-phase 50 Hz to single-phase 16 2/3 Hz for universal motor traction drives.

Joseph Slepian of Westinghouse invented the ignitron tube in 1933. It is a single-anode, pool-cathode metal-case gas tube, where an igniter (with phase control) initiates the conduction. The ignitron tube could be designed to handle high power at high voltage. The single-anode structure of the ignitron tube permitted inverse-parallel operation for ac voltage control for applications such as welding and heating control as well as bridge converter configurations popular in railway and steel mill dc drives, and SM speed control, which has used dc-link load-commutated inverters (LCI) and CCVs since the late 1930s.

Ignitron converters were also used in HVdc transmission systems in the 1950s until high-power thyristor converters replaced them in the 1970s. The first HVdc transmission system was installed in Gotland, Sweden, in 1954. The diode bridge converter configurations (known as Graetz circuits) were invented much earlier (1897) by the German physicist Leo Graetz using electrolytic rectifiers. (See "My M.S. Degree in Wisconsin.")

Hot-Cathode Gas Tube Rectifiers

The thyratron, or hot-cathode glass bulb gas tube rectifier, was invented by GE (1926) for low-to-medium power applications. Functionally, it is similar to a grid-controlled mercury-arc tube. Instead of a pool cathode, the thyratron tube used a dry cathode thermionic emission heated by a filament similar to a vacuum triode, which was widely used in those days. The tube was filled with mercury vapor; the ionization of this vapor decreased the anode-to-cathode conduction drop (for higher efficiency), which was lower than that of mercury-arc tube. The grid bias with phase-shift controlled conduction is similar to the pool cathode tube. The modern thyristor or silicon-controlled rectifier (SCR), which is functionally similar, derives its name from the thyratron. The diode version of the thyratron was known as the phanotron. One interesting application of the phanotron was in the Kramer drive, where the phanotron bridge replaced the rotory converter (1938) for slip power rectification. Thyratrons were popular for commercial dc motor drives, where the power requirement was low. E.F.W. Alexanderson, the famous scientist in GE Corporate Research and Development (GE-CRD) in Schenectady, installed a thyratron CCV drive in 1934 for a wound-field SM (WFSM) drive (400 hp) for speed control of induced draft fans in the Logan power station. This was the first variable-frequency ac drive installation in history.

Magnetic Amplifiers

Functionally, a magnetic amplifier (MA) is similar to a mercury-arc or thyratron rectifier. It uses a high-permeability saturable reactor magnetic core with materials such as permalloy, supermalloy, deltamax, and supermendur. A control winding with dc current resets the core flux, whereas the power winding sets the core flux to saturate at a "firing angle" and apply power to the load. The phase-controlled ac power could be converted to variable dc with the help of a diode rectifier. In the early days, MAs used copper oxide (1930) and selenium rectifiers (1940) until germanium and silicon rectifiers became available in the 1950s. Copper oxide and selenium rectifiers were bulky and had a large leakage current.

The traditional MAs used series or parallel circuit configuration. The advantages of MAs are their ruggedness and reliability, but the disadvantages are their increased size and weight. Germany was the leader in MA technology and applied it extensively in military applications [3] during World War II, such as in

MY UNDERGRADUATE DAYS

I was an undergraduate student in Bengal Engineering College (now Bengal Engineering and Science University), India, from 1952 to 1956. There was a large machines laboratory, where in our senior year, we were assigned machine experiments on Ward-Leonard speed control, Hopkinson's test (dc motor regeneration with a coupled dc generator), synchronization of an alternator on a three-phase bus with the three-lamp method, and Schrage motor speed control. Prof. Ralph Benedict from the University of Wisconsin came and taught course on mercury-arc rectifiers. We had two lab experiments on glass-bulb mercury-arc rectifiers. One was a single-phase full-wave diode rectifier with center-tapped transformer, where we used to start the arc through an auxiliary anode by tilting the bulb. The other was a six-phase half-wave grid-controlled rectifier, where the arc was initiated by a current pulse through an auxiliary anode.

MY M.S. DEGREE IN WISCONSIN

I pursued my master's degree at the University of Wisconsin, Madison, from 1958 to 1960. The university was very famous for its power program. Prof. Benedict was my thesis adviser who also taught my power electronics courses. There was an industrial electronics laboratory, where we conducted experiments on a thyratron dc motor drive and ignitron welding control. The term "power electronics" was unknown in those days but instead was known as "industrial electronics." Power electronics was introduced in the beginning of 1970s. I conducted my M.S. research on the study of diode bridge rectifier harmonics and their effects on the utility system.

naval ship gun control and V-2 rocket control. However, historically, Alexanderson was the pioneer in MA applications. He applied MA to radio-frequency telephony (1912), where he designed an HF alternator and used MAs to modulate the power for radio telephony. In 1916, he designed a 70-kW HF alternator (up to 100 kHz) at GE-CRD to establish a radio link with Europe. Even today, MAs are used to control the lights of the GE logo on top of building 37 in Schenectady, where Alexanderson used to work. The MA dc motor drives were competitors of the thyratron dc drives and popular for use in adverse environments. (See "My Research in Magnetic Amplifiers.")

Robert Ramey invented the fast half-cycle response MA in 1951, which found extensive applications particularly in low-power dc motor speed control, servo amplifiers, logic and timer circuits, oscillators (such as the Royer oscillator), and telemetry encoding circuits. Copper oxide and selenium applications for signal processing proved extremely important when modern semiconductor-based control electronics was in its infancy.

Power Electronics in the Modern Era

Power Semiconductor Devices

The modern solid-state electronics revolution began with the invention of transistors in 1948 by Bardeen, Brattain, and Schockley of Bell Laboratory. While Bardeen and Brattain invented the point contact transistor, Schockley invented the junction transistor. Although solid-state electronics originally started with Ge, it gradually transformed using with Si as its base. The modern solid-state power electronics revolution [4]–[7] (often called the second electronics revolution) started with the invention of the p-n-p-n Si transistor in 1956 by Moll, Tanenbaum, Goldey, and Holonyak at Bell Laboratory, and GE introduced the thyristor (or SCR) to the commercial market in 1958. Thyristors reigned supreme for two decades (1960–1980), even with the present popularity for high-power HVdc and LCI drive applications.

The word "thyristor" comes from the word "thyratron" because of the analogy of operation. Power diodes (both Ge and Si) became available in the mid-1950s. Starting originally with the phase-controlled thyristor, gradually other power devices emerged. The integrated antiparallel thyristor (TRIAC) was invented by GE in 1958 for ac power control. The gate turn-off thyristor (GTO) was invented by GE in 1958, but in the 1980s, several Japanese companies introduced high-power GTOs to the market. Bipolar junction transistors (BJTs) and field-effect transistors were known from the beginning of the solid-state era, but power MOSFETs and BJTs [bipolar power transistors (BPTs)] appeared on the market in the late 1970s. Currently, both GTOs and BPTs are obsolete devices, but power MOSFETs have become universally popular for low-voltage HF applications. The invention of the insulated-gate bipolar transistor (IGBT or IGT) in 1983 by GE-CRD and its commercial introduction in 1985 were significant milestones in the history of power semiconductors. Jayant Baliga was the inventor of the IGBT. However, initially, it had a thyristor-like latching problem and, therefore, was defined as an insulated-gate rectifier. Akio Nakagawa solved this latching problem (1984), and this helped the commercialization of the IGBT.

Today, the IGBT is the most important device for medium-to-high power applications. Several other devices, including the static induction transistor, the static induction thyristor, the MOS-controlled thyristor (MCT), the injection enhanced gate transistor, and the MOS turn-off thyristor, were developed in the laboratory in the 1970s and 1980s but did not ultimately see the daylight. Particularly for MCT development, the U.S. government spent a fortune, but it ultimately went to waste. The high-power, integrated gate-commutated thyristor (IGCT) was introduced by ABB in 1997. Currently, it is a competitor to the high-power IGBT, but it is gradually losing the race. Although silicon has been the basic raw material for current power devices, large-bandgap materials, such as SiC, GaN, and ultimately diamond (in synthetic thin-film form), are showing great promise. SiC devices, such as the Schottky barrier diode (1200 V/50 A), the power MOSFET (1200-V/100-A half-bridge module), and the JBS diode (600 V/20 A), are already on the market, and the p-i-n diode (10 kV) and IGBT (15 kV) will be introduced in the future. There are many challenges in researching large-bandgap power devices. (See "My Days at RPI and Research in Modern Power Electronics.")

Fortunately, in parallel with the power semiconductor evolution, microelectronics technology was advancing quickly and the corresponding material processing and fabrication techniques, packaging, device characterization, modeling, and simulation techniques contributed to the successful evolution of so many advanced power devices, their higher voltage and current ratings, and the improvement of their performance characteristics. Gradually, microelectronics-based devices, such as microcomputers/DSPs and application-specified integrated circuit

MY RESEARCH IN MAGNETIC AMPLIFIERS

I did my doctoral research at Calcutta University, India, with Ramey MAs from 1960 to 1965, when I began my career at Bengal Engineering College. Although thyristors were available at that time, Dr. Herbert Storm, a renowned authority in MAs at GE-CRD, advised me to work in this area and agreed to be my adviser remotely from Schenectady. MA analytical study was much more complex than that of thyristor converters. My research was somewhat hybridized with MAs (with silicon diodes), power transistors, and thyristors. My research projects were a magnetic servo amplifier for position control with a two-phase induction servomotor, multichannel telemetry encoding systems using MAs with transistors, and MAs with thyristors. The NASA Langley Research Center, United States, seriously, considered them for satellite-to-earth data transmission. From 1966 to 1971, before emigrating to the United States, I supervised a number of MA-based research projects.

(ASIC)/FPGA chips, became the backbone of power electronic system control.

Power Converters

Most of the thyristor phase-controlled line and load-commutated converters, commonly used today, were introduced in the era of classical power electronics. The disadvantages of line-side phase control are a lagging displacement power factor (DPF) and lower-order line harmonics. The IEEE regulated harmonics with the Standard IEEE-519 (1981), whereas Europe adopted the IEC-61000 standard, which was introduced in the 1990s. The current-fed dc link converters became very popular for multi-MW WFSM drives from the 1980s. The initial start-up method of the motor (building sufficient CEMF for load commutation) by the dc-link current interruption method was proposed by Mueller et al. (1979) and is popular even today. For a lagging DPF load (such as IM), the inverter required forced commutation. The auto-sequential current inverter (ASCI) using forced commutation was proposed by Kenneth Phillips in 1971. This topology became obsolete with the advent of modern self-commutated devices. The thyristor phase-controlled CCVs (with line commutation), were very popular from 1960 until 1995, when multilevel converters made them obsolete. The traditional CCVs used the blocking method, but Toshiba introduced the circulating current method in the 1980s to control the line DPF. The dual converter for a four-quadrant dc motor drive was popular long before that.

The advent of thyristors initiated the evolution of the dc-link voltage-fed class of thyristor inverters for general industrial applications [8]–[13], particularly for IM drives. The voltage-fed converter topology is the most popular today and will possibly become universal in the future. A diode rectifier (Graetz bridge) usually supplies the dc link, and a force-commutated thyristor bridge inverter was the usual configuration. From the 1960s, the era of the thyristor forced commutation techniques started, and William McMurray of GE-CRD was the pioneer in this area. (See "My Project with Bill.") He invented forced commutation techniques [14], known as the McMurray inverter (1961), the McMurray–Bedford inverter (1961), ac switched commutation (1980), and so on, which will remain as the most outstanding contributions in the history of power electronics. Gradually, self-commutated devices, such as power MOSFETs, BPTs, GTOs, IGBTs, and IGCTs, appeared in the 1980s and replaced a majority of thyristor inverters.

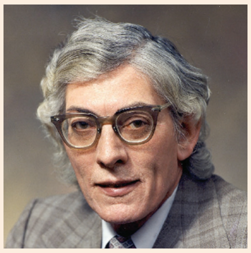
The originally introduced voltage-fed inverters (VFIs) with square (or six-stepped) wave output had a rich harmonic content. Therefore, the pulsewidth modulation (PWM) technique was used to control the harmonics as well as the output voltage. Fred Turnbull of GE-CRD invented the selected harmonic elimination PWM in 1963, which was later generalized by Patel and Hoft (1973) and optimized by Indri and Buja (1977). However, the sinusoidal PWM technique, invented by Schonung and Stemmler (1964), found widespread applications. Since motor drives mostly required current control, Allen Plunkett of GE-CRD developed the hysteresis-band (HB) sinusoidal current control in 1979. This was improved to the adaptive HB method (1989) by myself to reduce the harmonic content. The space vector PWM (SVM) technique for isolated neutral load, based on the space vector theory of machines, was invented by Pfaff, Weschta, and Wick in 1982. The SVM, although very complex, is now widely used. The front-end diode rectifier was gradually replaced by the PWM rectifier (the same as inverter topology), which allowed for four-quadrant drive capability and sinusoidal line current at any desired DPF. High-power GTO converters could be operated in multistepped mode because of the low switching frequency. The PWM rectifier operation modes allowed for the introduction of the static VAR compensator. Current-fed self-commutated GTO converters for high-power applications that required a capacitor bank on ac side were introduced in the 1980s. The performance of this type of dc-link dual PWM converter system is similar to that of the voltage-fed converter system. (See "My GE-CRD Experience.")

A class of ac–ac converters, called matrix converters (or direct PWM frequency converters), was introduced by Venturini (they are often called Venturini converters) in 1980 using inverse-parallel ac switches. My invention, a inverse-series transistor ac switch (1973), is now universally used in matrix converters. This converter topology has received a lot of attention in the literature, but so far, there have been very few industrial applications. Soft-switched dc–ac power conversion for ac motor drives was proposed by Deepak Divan (1985) and subsequent researchers but hardly saw any daylight. However, soft-switched HF link power conversion has been popular for use in low-power dc–dc converters since the early 1980s.

MY DAYS AT RPI AND RESEARCH IN MODERN POWER ELECTRONICS

I emigrated from India in 1971 and started my career at Rensselaer Polytechnic Institute (RPI) as a faculty member in modern power electronics. GE-CRD initiated this program, but getting an offer from RPI while I was in India was not easy. To test my knowledge, the department chairman asked me to submit four doctoral research topics and formulate a full senior/graduate course in power electronics. This was quite a challenge for me. However, GE-CRD examined my submission and approved it. As RPI was a private university with a great reputation, I found that the students were extremely brilliant and constantly tested my knowledge in power electronics. At that time, the only other university in the United States with a power electronics program was the University of Missouri, Columbia. After joining RPI, I got a part-time consulting project from GE-CRD on thyristor HF link power conversion, which was quite a challenge for me. I left RPI to join GE-CRD on a full-time basis in 1976.

MY PROJECT WITH BILL



Dr. William McMurray, the guru of power electronics (1926–2006).

Bill McMurray is the founding father and guru of power electronics, and the world bows to him with deep respect. All of his papers (particularly those on thyristor forced commutation techniques) are considered classic contributions to power electronics. His research set the stage for the modern power electronics evolution. He was in GE-CRD for 35 years (from 1953 to 1988). Bill received the honorary doctor of law degree from Concordia University, Canada, in 1986. He became an IEEE Fellow in 1980 and a Life Fellow in 1994. He received the IEEE Newell Award (1978), the IEEE Lamme Medal (1984), and the IEEE Millennium Medal (2000) for his research contributions. He authored the book *The Theory and Design of Cycloconverters* (MIT Press, 1972) and was a contributing author in the historic book [14] *Principles of Inverter Circuits* by Bedford and Hoft (New York: Wiley 1964).

I had the opportunity to work with Bill at GE-CRD. My project with him was an analysis and simulation of an ASCI inverter. Bill was a dedicated scientist and rarely talked with anybody. Although I sat at the table next to his, I had to make appointment to talk to him. He deeply loved mathematics and filled page after page with complex equations, which were strewn all over his table and the floor. After a generalized analysis, he loved to draw normalized graphical plots. He was a chain smoker, and our room was filled with deep smoke all the time. A young secretary sitting in the same room used to call him "an awful person." In the later part of his life, he suffered from emphysema, which was the cause of his death. Bill gave me inspiration. I learned from him that "research ideas do not necessarily come within the 8 a.m. to 5 p.m. work day in office. The thoughts linger most of the time beyond the office hours, and often new ideas come when I am taking bath, walking alone in the evening, or even in the midnight when I suddenly wake up with the flash of new idea. There is no difference between scientific research and transcendental meditation" [19].

For high-voltage, high-power voltage-fed converter applications, Akira Nabae et al. invented the neutral-point clamped (NPC) multilevel converter in 1980 that found widespread applications in the 1990s and recently ousted the traditional thyristor CCVs. Gradually, the number of levels of the converter increased, and other types, such as the cascaded H-bridge or half-bridge and flying capacitor types, were introduced. Currently, the NPC topology is the one most commonly used.

Motor Drives

The area of motor drives [15]–[17] is intimately related with power electronics, and it followed the evolution of devices and converters along with the PWM, computer simulation, and DSP techniques. The WRIM slip power control and load-commutated WFSM drives, introduced early in the gas tube age, have been discussed previously. However, historically, ac machines were popular in constant-speed applications. During the thyristor age (the 1960s through the 1980s), variable-speed ac drives technology advanced at a rapid rate. Early in the thyristor age, variable-voltage constant-frequency IM drives were introduced using three-phase antiparallel thyristor voltage controllers, and Derek Paice (1964) of Westinghouse was the pioneer in this area. The so-called Nola speed controller proposed by NASA in the late 1970s is essentially the same type of drive. However, the disadvantages of the drive are loss of torque at low voltage, poor efficiency, and line and load harmonics. The solid-state IM starter often uses this technique. The introduction of the McMurray inverter and the McMurray–Bedford inverter using thyristors essentially started the revolution for variable-frequency motor drives. With variable-frequency, variable-voltage sinusoidal power supply from a dc-link voltage source PWM inverter, rated machine torque was always available and the machine had no harmonic problems. The dc link voltage could be generated from the line either with a diode or a PWM rectifier. This simple open-loop volts/hertz control technique became extremely popular and is commonly used today. To prevent the speed and flux drift of open-loop volts/hertz control and improve the stability problem, closed-loop speed control with slip and flux regulation

MY GE-CRD EXPERIENCE

In 1976, I decided to transition my career to GE-CRD. After a 16-year university career, this was quite a challenge. My motivation was to gain real-world, hands-on knowledge in power electronics and experience large practical projects. In those days, GE-CRD was the world's top research center in power electronics. It was like Bell Laboratory where the transistor was invented. My office was in the historic building 37, where Alexanderson, Gabriel Kron, Philip Alger, and others had offices. Power electronics professionals from all over the world used to visit us in Schenectady. It was a thrilling experience to see so many world-renowned scientists across the hall. After joining GE, I started working with McMurray on an ASCI inverter. During most of my time at GE (until 1987), I was involved with electric vehicle (EV) and hybrid vehicle projects. This was the first major initiative by the U.S. government after the Arab oil embargo in the 1970s. I was the principal engineer for microprocessor/DSP-based control development, which was a very difficult subject at that time for a power electronics engineer. Our first EV project (ETV1) with a power transistor chopper and dc motor drive (1978) was very successful. We demonstrated ETV1 before Queen Elizabeth II of England. My last project was EV drive (ETX II) control with IPM synchronous motor. Gradually, the interior permanent magnet synchronous motor drive was accepted for EV drives all over the world.

MY EXPERIENCE AT THE UNIVERSITY OF TENNESSEE

I decided to switch back to a university career (which was my original home) in 1987 after spending 11 years in GE-CRD. In parallel, I also started working as chief scientist of the newly established Power Electronics Applications Center at the Electric Power Research Institute. Fortunately, a large number of visiting professors and scholars from abroad came to work with me, with the financial support of their governments. All of them were brilliant scholars. Most of them wanted to do research in the emerging AI techniques, particularly in fuzzy logic and neural network applications. Some of my projects in the lab were: 1) a soft-switched inverter for motor drives, 2) high-frequency non-resonant link power conversion using MCTs, 3) fuzzy control of dc and IM drives, 4) a fuzzy-controlled wind generation system with efficiency optimization, 5) neural network–based drive feedback signal estimation and SVM of multilevel converters, 6) converter fault investigation, 7) an automated IM drive control design by expert system, and 8) sensorless vector control of IM. I traveled abroad extensively to give tutorials, invited seminars, and keynote addresses. During this period, I also completed two other text books.

was used in the 1970s and early 1980s. Current-fed thyristor and GTO converters for IM drives were promoted during the same period. The advent of modern self-commutated devices considerably improved the performance of VFI drives.

The introduction of vector or field-oriented control brought a renaissance in the history of high-performance ac drives. Hasse (1969) introduced the indirect vector control, whereas the direct vector control was introduced by Blaschke (1972). The vector control and estimation depended on synchronous reference frame $(d^e - q^e)$ and stationary reference frame $(d^s - q^s)$ dynamic models of the machine. The $d^e - q^e$ model was originally introduced by Park (1929) for synchronous machines and was later extended to IM by Gabrail Kron of GE-CRD, whereas the $d^s - q^s$ model of IM was introduced by Stanley (1938). Because of the control complexity, vector control has been applied in industry since the 1980s in microcomputer/DSP control. The microcomputer was invented by Intel in 1971, and the technology started advancing dramatically with the introduction of the TMS320 family in the 1980s by Texas Instruments. Recently, the powerful ASICs/FPGAs along with DSPs are almost universal in the control of power electronics systems. In 1985, Iso Takahashi invented an advanced scalar control technique called direct torque control or direct torque and flux control, which was to some extent close to vector control in performance. Gradually, other advanced control techniques, such as model-referencing adaptive control, sensorless vector control, and model predictive control, emerged. Currently, AI techniques, particularly fuzzy and artificial neural networks, are advancing the frontier of power electronics. Most of the control techniques developed for IM drives were also applicable to SM drives. However, the interest in SRM drives is gradually dying after the surge of literature during the 1980s and 1990s.

Conclusion

This article gives a brief historical review of the power electronics evolution that includes electrical machines, mercury-arc rectifiers, gas tube electronics, MAs, power semiconductor devices, converter circuits, and motor drives. Important inventions with the name of the inventor and the year are given wherever possible. It is important to note that inventions are generally developed by a number of contributors working over a period of time. Since I started my career practically at the beginning of the power electronics age and aggressively pursued the technology progression throughout my entire career, a few relevant inserts describing my experiences have been included. (See "My Experience at the University of Tennessee.") An insert with a photo of Bill McMurray, the guru of power electronics, is an especially significant part of this article.

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