by Bimal K. Bose

Power Electronics

My Life and Vision for the Future

Power electronics has ushered in a new kind of industrial revolution in the 21st century because of its important roles in energy conservation, renewable energy systems (RESs), bulk energy storage, electric and hybrid electric vehicles, and smart grid applications besides its traditional role in high-efficiency energy systems. Future advances in power electronics will occur mainly in two directions: wide-bandgap (WBG) power semiconductor devices and complex smart grid systems.

Power electronics, a well-known technology, is concerned with the conversion and control of electrical energy at high efficiency with switching-mode power semiconductor devices, and its applications include dc and ac power supplies, electrochemical processes, heating and lighting control, electronic welding, power line VAR and harmonic compensation, high-voltage dc (HVdc) systems, flexible ac transmission systems (FACTSs), photovoltaic (PV) and fuel cell power conversion, solid-state circuit breakers, high-frequency heating, and motor drives. Power electronics is said to have ushered in a new kind of industrial revolution because of its important role in energy conservation, RESs, bulk energy storage, EVs and HEVs, and smart grid applications in addition to its traditional roles in industrial automation and high efficiency energy systems.

The 21st century is often defined as the golden era of power electronics after the main technology evolution stabilized in the later part of the past century, although the momentum of technology evolution will continue in this century. Often, it is said that power electronics has brought in the third industrial revolution, where the first revolution was brought by the invention of heat engines and the second revolution was brought by the invention of transistors. In this century, power electronics will play significant role in the green energy revolution and help solve the problems of global climate change, which have devastating effects on our society. As environmental regulations are tightened and energy prices increase, power electronics applications will proliferate everywhere—industrial, commercial, residential, transportation, aerospace, military, and utility systems.

THE 21ST CENTURY IS OFTEN DEFINED AS THE GOLDEN ERA OF POWER ELECTRONICS AFTER THE MAIN TECHNOLOGY EVOLUTION STABILIZED IN THE LATER PART OF THE PAST CENTURY.

In this article, a brief review of power electronics evolution and prognosis for the future will be given based on my knowledge and experience over the span of more than 50 years. Suffice it to say that technology prediction is always difficult because our past knowledge can only be projected to give a vision for the future. Any new invention may alter the course of a technology, which has happened many times in the history of power electronics. Since I devoted my entire life to the field of power electronics, my personal journey through it will be embedded briefly within the contents of this article [9]. Again, it is difficult to give a future perspective of this vast field in the

MY GRADUATE EDUCATION IN THE UNIVERSITY OF WISCONSIN (1958–1960)

I was selected by the Government of India under the United States Agency for International Development Program (then known as the *Technical Cooperation Mission*) to study for an M.S. degree at the University of Wisconsin, Madison. I had to sign a contract that after the completion of my studies, I would have to serve in an Indian university for a period of three years. The University of Wisconsin had a large industrial electronics laboratory, where there were experiments on thyratron dc motor drives, ignitron welding controls, high-power polyphase mercury-arc rectifiers, and so on. My research was the investigation of line current harmonics with polyphase rectifier loads. In addition to these studies, I was given intensive training on engineering education.

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several pages of this article. The areas of power semiconductor devices, power converters, and machine drives, which are the main components of power electronics, will be covered in this article. In addition, some discussion on the role of power electronics in the smart grid and RESs as well as in climate change problems will also be included.

IN THIS CENTURY, POWER ELECTRONICS WILL PLAY SIGNIFICANT ROLE IN THE GREEN ENERGY REVOLUTION AND HELP SOLVE THE PROBLEMS OF GLOBAL CLIMATE CHANGE.

Classical Power Electronics

The history of classical power electronics [1] began at the dawn of 20th century (1902) with the invention of the glass-bulb mercury-arc rectifier by the American inventor Peter Cooper Hewitt. He later modified glass bulbs by steel tank for higher power. The introduction of the grid by Langmuir (1914) permitted conversion as well as control of electrical power. Slepian later introduced ignitron converters in 1933. The hot-cathode gas tube thyratron rectifier was invented by GE in 1926. Electrical machines, in fact, have a longer history, and many conversion and control functions were possible with the help of machines. The advent of machines in the 19th century and the commercial availability of electrical power started around the same time.

The War on Currents (ac versus dc) was started by Thomas Edison (1847–1931) and Nikola Tesla (1856–1943), but history eventually favored the superiority of ac for general industrial applications. The era of magnetic amplifiers (MAs) with saturable core reactors (using magnetic materials like Deltamax, Supermalloy, and so on) started during the War on Currents and permitted similar conversion and control functions. The ruggedness and reliability of MAs proved very important for military applications. It is interesting to note that E.F.W. Alexanderson of GE Corporate Research and Development, Schenectady, New York, used the MA technology to design and build a 70-kW, 100-kHz alternator to establish a radio communication link between the United States and Europe.

MY DOCTORAL STUDIES AND RESEARCH IN MAs (1960–1971)

After returning to India, I joined the Indian Institute of Engineering Science and Technology Shibpur (IIEST Shibpur) and started teaching on industrial electronics, advanced electrotechnology, and hydroelectric plants. Simultaneously, I started my doctoral studies in projects related to MAs. Dr. Herbert Storm, an internationally known expert in MAs in GE Corporate Research And Development (GE-CRD), inspired me to do research in this area and agreed to advise me remotely on my projects. My research projects were somewhat of a hybrid, using Deltamax saturable cores, silicon (Si) power diodes, bipolar junction transistors (BJTs), and thyristors. My projects were magnetic servo amplifiers for position control with two-phase induction servomotors and multichannel telemetry encoding systems using Ramey MAs with BJTs and thyristors. After the completion of my Ph.D. degree, I did a number of research projects with graduate students in MAs before emigrating to the United States in 1971. My first article was “Electronic speed control of motors,” published in 1962 in the *Journal of the Institution of Engineers (India)* [S1]. The term *power electronics* was introduced in 1960s after the invention of the thyristor.

REFERENCE

[S1] B. K. Bose, “Electronic speed control of motors,” *J. Inst. Eng. (India)*, pp. 172–182, Sep. 1962.

The Era of Modern Power Electronics

Power Semiconductor Devices

The era of modern power electronics started with the advent of power semiconductor devices, which constitute the heart of power electronics. In fact, the modern power electronics evolution has been possible primarily due to device evolution. Of course, the advent of novel converter topologies, pulsewidth modulation (PWM) techniques, analytical and simulation methods, advanced CAD tools, and control and estimation techniques, along with digital control hardware and software, contributed to this evolution. The era of solid-state electronics started with the invention of transistors by Bell Laboratory in 1948, and the same laboratory also invented the PNPN-triggering thyristor or silicon (Si)-controlled rectifier (SCR) in 1956. GE commercially introduced the thyristor in 1958. Si power diodes appeared slightly before in 1956.

The advent of SCRs essentially started the modern power electronics evolution. Then, the other power semiconductor devices, such as the TRIAC, gate turn-off thyristor (GTO), power bipolar junction transistors (BJTs), and power MOSFETs, gradually came. The invention of the insulated-gate bipolar transistor (IGBT) by GE was a significant milestone in the history of power semiconductors. It is interesting to note that initially, IGBTs had a thyristor-like latching problem, and the device was known as an *insulated-gate rectifier (IGR)*. Akio Nakagawa of Japan solved the latching problem and helped the commercial introduction of IGBT. The integrated gate-commutated thyristor (IGCT), which is basically a hard-driven GTO, was invented by ABB. In high-power applications, IGBTs and IGCTs are close competitors, but IGBTs are now generally preferred.

We are now on the verge of a new era of WBG power semiconductor devices, such as Si carbide (SiC) and gallium nitride (GaN), that promise higher power with higher efficiency and higher frequency of power electronic apparatus. The commercial introduction of SiC and GaN transistors in 2010 and 2015, respectively, was another significant milestone in the history of power semiconductor devices. Their applications are now growing extensively. These, along with the next generation ultra-WBG (UWBG) devices, will bring a renaissance in power electronics.

Table 1 summarizes the material property comparison [2] of Si, 4H-SiC, and GaN. The table also includes UWBG materials like gallium oxide (Ga_2O_3) and diamond. The other potential UWBG materials, like boron nitride (BN) and aluminum-gallium-nitride (AlGaN), are not included in the table.

Currently, the 4H-SiC structure is used for device manufacturing due to its higher carrier mobility. Note that the bandgap of SiC and GaN is typically three times higher than Si, giving breakdown field strengths of these materials that are 10 times higher than Si. This means that these devices can be built with a higher blocking voltage, lower leakage current, higher T_J, and higher switching frequency. The thinner and more highly doped drift layer of SiC devices leads to a lower drift resistance and lower saturation voltage, and therefore, a low conduction loss. For a GaN device (which has a lateral structure unlike SiC), the lower conduction loss is contributed by high-electron mobility [called *high-electron mobility transistor* (*HEMT*)] and higher saturation velocity. The higher thermal conductivity of SiC permits efficient thermal management.

However, the thermal conductivity of GaN is low and comparable to that of Si, but lower on-state losses make this problem less severe. The UWBG materials, like Ga_2O_3, diamond, and so on, have a higher breakdown field, and their properties are also listed in Table 1. Note that the thermal conductivity of diamond is very high, whereas this parameter is very low for Ga_2O_3. Diamond appears to be the ultimate material because of its wider bandgap, higher carrier mobility, and higher thermal conductivity. However, diamond is an extremely hard material. The exploration of the diamond power semiconductor is very challenging and needs the coordinated efforts of material scientists, chemical engineers, physicists, and electrical engineers. A specialist in this area comments:

> Diamond has a long way to go, First, we need to develop a low-cost large area single crystal growth technology that produces wafers with a low density of crystal defects. Then, there are manufacturing challenges to overcome since it is the hardest material. For the near future, we are blessed with SiC and GaN – we will have a huge number of challenges to solve in these two critical material technologies [2].

Table 2 shows the detailed comparison of Si, 4H-SiC, and GaN enhancement-mode power FETs [2]. The SiC MOSFET is a fast-switching voltage-controlled majority carrier unipolar device like Si MOSFET with a double-diffused metal-oxide-semiconductor (DMOS) structure. With the smaller thickness of the N-drift layer (because of the high breakdown field) and higher conductivity of the N-channel, the device has a higher voltage capability and smaller conduction drop than Si MOSFET. These properties also contribute to a higher

IMMIGRATION TO THE UNITED STATES AND START OF RESEARCH CAREER IN RENSSELAER POLYTECHNIC INSTITUTE IN MODERN POWER ELECTRONICS (1971–1976)

Going to the United States and settling in a reputed university was my lifelong ambition. I decided to emigrate to the United States in 1971 and start a new career at Rensselaer Polytechnic Institute (RPI). I joined RPI as an associate professor in electrical engineering with teaching and research in modern power electronics. The GE-CRD in Schenectady initiated this program, but getting an offer from RPI while working in India was not easy for me. The approval letter from RPI helped me to get my emigration visa (green card) quickly. RPI was a reputable private university, and the students were very brilliant. After joining RPI, I got a part-time offer from GE-CRD with a project on a thyristor high-frequency link cycloconverter. During my RPI career for five years, I did a number of innovative projects that included: developing a transistor ac switch for matrix converters; TRIAC speed control of induction motors; the series/parallel operation of TRIACs in converters; three-phase ac power control with transistors; a thyristor-saturable core self-oscillating Royer inverter; the phase-locked-loop speed control of dc motors; and so on. My GE project was extremely complex, but fortunately, it turned out to be very successful. As a reward, GE-CRD offered me a job in 1976, which I could not refuse.

TABLE 1 – A COMPARISON OF THE PROPERTY OF Si WITH WBG (4H-SiC, GaN), AND UWBG (Ga_2O_3 AND DIAMOND) MATERIALS.

	Si	4H-SiC	GaN	Ga_2O_3	DIAMOND
Bandgap E_g (eV)	1.12	3.26	3.4	4.8	5.5
Breakdown field E_B (V/cm)X10^6	0.3	3	3.5	8	10
Electron mobility u_n (cm^2/Vs)	1,420	1,000	2,000	400	2,200
Hole mobility u_p (cm^2/Vs)]	600	100	200	100	850
Electron saturation velocity (10^6 cm/s)	10	22	25	–	–
Thermal conductivity (W/cm °C)	1.5	4	1.3	0.2	22
Saturation drift velocity versus (10^{6}cm/s)	10	20	25	–	–
Relative dielectric constant E_s	11.8	9.7	9.5	–	–

switching frequency. It has a reverse-conducting body diode, but the recovery current and recovery time are low due to the short minority carrier lifetime (like the SiC Schottky barrier diode) and are mainly contributed by the discharge of tiny junction capacitances. For this reason, the bypass diode is often omitted. The saturation resistance ($R_{DS(ON)}$) is reduced by a higher V_{GS} but increases at a higher junction temperature (positive temperature coefficient). Trench technology (developed by Infineon) can reduce conduction channel resistance of all the devices to improve the conduction efficiency (called CoolMOS, CoolSiC or CoolGaN).

Because of WBG, the device can operate at a higher T_J (up to 200 °C). The cooling system design is less expensive due to the low thermal resistance of the device. A normally on junction field-effect transistor (JFET) with the cascoded connection of low-voltage Si MOSFET is also available, but normally off enhancement-mode devices are preferred. Currently, up to 1,700-V/350-A devices are available commercially. Higher-voltage SiC MOSFETS will have an excessive conduction loss. For this reason, higher-voltage, higher-power devices are bipolar (such as IGBT, GTO, thyristors, and so on) with conductivity modulation. For example, 15-kV SiC IGBTs have been undergoing laboratory testing for some time.

The GaN HEMT is a field-effect planer device with lateral current flow and extremely high efficiency. The active region of the transistor is fabricated using GaN and AlGaN semiconductor materials on top of a Si substrate. The transition layers are grown for the differences of the thermal expansion coefficients between Si and GaN. The conduction path between the drain and source contacts is called *Two-dimensional* (*2D*) *electron gas* (*2DEG*) and is formed at the heterojunction between the GaN and AlGaN layers. The 2DEG is enhanced or depleted by the potential difference between the gate and the 2DEG below it. The HEMT conducts in the reverse direction without any body diode, i.e., there is no recovery loss. Matrix converter ac switches can be easily built with an inverse-series connection of GaN HEMT (no bypass diodes are needed) devices with a very low conduction loss.

TABLE 2 – AN APPROXIMATE COMPARISON OF Si, 4H-SiC, AND GaN ENHANCEMENT-MODE POWER FETs.

	Si	**4H-SiC**	**GaN**
Voltage and current Ratings (Selected device for comparison)	30 V/15 A* (dc)	650 V/110 A† (dc)	600 V/31 A‡ (dc)
Present power capability	1.2 kV/50 A	1,700 V/350 A	650 V/60 A, 1,200 V/30 A
Voltage blocking	Asymmetric	Asymmetric	Asymmetric
Gating	MOSFET	MOSFET	FET
Junction temperature range °C	–55 to +175	–55 to 200	–55 to 150
Safe operating area	Square	Square	Square
Static on-resistance $R_{DS(on)}$ mΩ 25°C	8.6	18	70
Switching frequency range, typical	Up to 1 MHz	Up to 1 MHz	Up to 3 MHz
dV/dt (V/ns)	–	50	200
Turn-on time (ns)	55	64	18
Turn-off time (ns)	35	74	29
Antiparallel diode	Yes	Yes	No
Reverse recovery loss	Yes	Yes	No
Snubber	Yes or no	Yes or no	Yes or no
Protection	Gate control	Gate control	Gate control
Thermal resistance R_{thjc} °C/W	5.9	0.31	1
Applications	Low voltage low power, SMPS, BLDM	VSC for EV, battery charger, PV, wind, and so forth	VSC for EV, PV, wind, and so forth
Comments	Very mature	Fast body diode	Ultrafast switching, no body diode, extremely low parasitic capacitances

*IR-6723M2DTR (dual package).
†ST-SCTW90N65G2V.
‡Infineon IG060R070D1 CoolGaN.
BLDM: brushless DC motor; VSC: voltage source converter.

In summary, the GaN lateral transistor structure permits very low gate and output storage charges, and correspondingly, very high switching frequency. Normally on GaN JFET is also available in a cascode structure with a series connection of Si MOSFET. Currently, 650-V/60-A, 1,200-V/30-A enhancement FETs are available, but higher-voltage, higher-power vertical devices are under development and will be available in the future. Again, in the future, bipolar devices with a higher power rating will also be available. An example application of an 80 kW GaN-based converter [3] for utility energy storage application indicates 95% less loss compared to Si IGBT and 85% less loss compared to SiC MOSFET.

In summary, the following general comments can be made for power semiconductor evolution:

- The gradual obsolescence of phase-control devices (thyristors and TRIACs) will occur.
- Si-based BJTs and GTOs are already obsolete.
- Insulated-gate self-controlled devices (power MOSFET, IGBT, and so on) will dominate.
- Si power MOSFET will remain universal for low-voltage, low-power, and high-frequency applications [switch-mode power supplies (SMPS), brushless DC motor (BLDM), and so on].

- High-power IGCTs are being replaced by IGBTs.
- WBG power devices will be accepted universally in high- and medium-power converters.
- SiC devices will dominate for high-voltage, high-power applications.
- GaN devices are currently for medium power and will grow for high power in the future.
- SiC and GaN devices essentially constitute the near-term technology.
- The advent of UWBG power semiconductor devices in the next generation, such as Ga_2O_3, BN, and diamond, will provide significantly more improvement in voltage, frequency, and efficiency ratings of the devices, with the corresponding size miniaturization and higher-temperature operation in power electronics. Of course, the higher-temperature operation of passive circuit components, device packaging, and control system components is mandatory in high-temperature power electronics.
- Diamond appears to be the ultimate material that may be explored far in the next generation.
- Intelligent, integrated power modules will be increasingly available.
- The general trend is the integration of converter, control, and protection.

Power Converters

Power electronic converters are generally constituted by a matrix of controllable power semiconductor switches that perform conversion as well as control of electrical power. Traditionally, most of the phase-controlled line and load-commutated converters (LCCs) (including cycloconverters), which have been commonly used in recent years, evolved in the classical power electronics era. Their popular applications today include thyristor-based high-power, multimegawatt (multi-MW) HVdc converters in transmission systems and LCC synchronous motor drives. The advantages of this class of converters are simple topology, very high efficiency, and simplicity of control. The high efficiency is essentially contributed by zero-current soft-switching.

However, the disadvantages are poor line displacement power factor, poor line power quality, sluggish control response, and the possibility of commutation failure due to line transients. The commutation failure in the LCC-wound field synchronous motor (WFSM) drive generates a large and dangerous pulsating torque in the machine. [Personal note: I was once involved in consulting on the failure of a 12-MW dual-cycloconverter (CCV)-WFSM gold-ore-grinding mill drive system in the West Australia (Kalgoorlie) grid [4], where commutation failure generated a large oscillatory pulsating torque, causing extensive damage to the machine and the ring gear system.] The harmonic standards of the IEEE (IEEE-519) and Europe (IEC-61000) were formulated to limit the line harmonics. The line harmonics in the phase-controlled converter (PCC) can be attenuated by multipulsing with a phase-shifting transformer or by using active filters.

ANY NEW INVENTION MAY ALTER THE COURSE OF A TECHNOLOGY, WHICH HAS HAPPENED MANY TIMES IN THE HISTORY OF POWER ELECTRONICS.

The line-lagging DPF problem can be solved by a static synchronous compensator (STATCOM) [static VAR compensator (SVC)]. The advent of a self-controlled thyristor inverter by forced commutation initiated the evolution of dc-link voltage-source converters for general industrial applications, including ac motor drives. William McMurray of GE was the pioneer in this area. Gradually, the advent of self-controlled devices replaced thyristor converters. Different types of PWM techniques,

MY 11 YEARS IN THE GE CORPORATE RESEARCH LAB (1976–1987)

Having spent 16 years of my career in the university setting so far, I always felt that I had a big gap in my expertise in power electronics. I had rarely worked with large power electronic converters for industrial applications. In those days, GE-CRD was the world's top research center in power electronics. It was like Bell Lab, where transistor was invented. The images of Thomas Edison and Charles Steinmetz were everywhere in GE. My office was located in the historic Building 37, where E.F.W. Alexanderson, Gabriel Kron, Philip Alger, and so on had their laboratories. GE-CRD was then considered as the ivory tower of power electronics worldwide, and power electronic professionals from all over the world used to visit us in Schenectady. It was a thrilling experience to meet so many world-renowned scientists across the hall. After joining GE, I started working with Bill McMurray on a current-fed Auto Sequential Commutated inverter and was located in the same office. McMurray was the founding father and guru of power electronics, and the whole power electronic world bowed to him with deep respect.

During most of my time in GE, I was involved with EV and HEV projects. The EV/HEV development was the first major initiative by the U.S. Government Department of Energy after the Arab oil embargo in the 1970s. I was the principal engineer for microprocessor/digital signal processor (DSP) control development. Our first EV (ETV1) with a power transistor chopper and dc motor drive was very successful and was demonstrated before Queen Elizabeth II of England. Our last EV project (ETX II) [2] was based on an interior permanent-magnet synchronous motor (IPM-SM) drive. Gradually, IPM motor-based EV drives were accepted all over the world. My other GE projects were: a linear inductor motor drive for railroad propulsion; a switched reluctance motor (SRM) drive; a residential PV system maximum power point tracker control; a sliding mode control of induction motors (IMs); a scalar decoupled control of IM; an adaptive hysteresis-band control of an IPM motor; and so on. I published my first textbook on power electronics and ac drives in 1986 with Prentice Hall while working in GE.

such as sinusoidal pulse width modulation, HB, selected harmonic elimination, and space vector modulation, also arrived to control output voltage with improved harmonic quality. The PWM active rectifier was introduced to control line harmonics as well as DPF.

Dual PWM converters, particularly with the neutral-point-clamped type, ousted the CCVs. Active filters, which are used with PCC and diode rectifiers, are getting obsolete. The SVCs/STATCOMs are extremely important elements in power grids for lagging DPF correction of load and line P and Q control with the help of FACTS. FACTS is an extremely important element in the future smart grid. Converter soft-switching, although extremely popular in high-frequency link SMPS, is not useful in general high-power electronics, including motor drives. The matrix converter (MC), introduced in 1980s, has an attractive topology, but its future is slim in the author's opinion in spite of the advent of simple- and high-efficiency GaN ac switches. MCs have been on and off many times in the industry. The modern modular multilevel converters (MMCs), particularly using cascaded H-bridge and half-bridge (defined as MMC) topologies, are very important. The MMCs, particularly with SiC and other WBG devices, are important in utility systems with 50/60-Hz applications in HVdc converters, STATCOMs, FACTS, and variable frequency motor drives where the current is low at lower frequencies.

In summary, the following general comments can be made for converter technology evolution:

- Phase-controlled thyristor-based converters will be totally obsolete in the future.
- Voltage source converters are becoming universal.
- Soft-switched voltage source converters, particularly for motor drives and other high-power applications, show no future promise.
- Matrix converters, in spite of rich literature, are not expected for drives and other applications.
- Z-source converter [Z-source inverter (ZSI) or quasi-ZSI] applications in industry are questionable.
- Model predictive control (MPC) applications in industry are questionable.
- Multilevel MMC type (with half-bridges) converters, particularly with SiC (and other WBG and future UWBG devices), have tremendous promise for high-power applications. A lot of research is yet needed for motor drive applications.
- There is an increasing trend of real-time simulation of power electronic systems with hardware-in-loop testing.
- Converter technology, in general, is approaching saturation. Future emphasis will be on integration, automated design, and advanced control by digital signal processors (DSPs) and field-programmable gate arrays.

Motor Drives

The area of motor drives is closely associated with the evolution of power electronics, i.e., the evolution of devices, converters, control, estimation, modeling, simulation, and hardware/software implementation tools. Historically, between the two classes of dc and ac drives, the ac drives, particularly the cage-type induction motors, were traditionally used in constant-speed application, whereas dc drives were used in variable-speed applications. Although dc drives are still widely used in industry, they are tending to become obsolete because of their characteristic disadvantages. The technology advancement of power electronics has permitted variable-frequency, variable-speed ac drives (both induction and synchronous), and they are now used extensively in industry. The cage-type induction motor drives are very common because the machines are cheaper, more rugged, and reliable.

However, the efficiency of permanent-magnet SM (PMSM) drives with a high-energy neodymium-iron-boron magnet is higher, although the machine is more expensive, which makes the lifecycle cost lower. In high-power drives, WFSM drives will remain popular because of the performance advantages with field control. Thyristor-based load-commutated inverter drives are being increasingly replaced by two-sided multilevel converters. In this context, it can be easily predicted that switched reluctance motor (SRM) drives will be totally obsolete for industrial applications. It is unfortunate that so much effort has been wasted on SRM drive technology over such a long time. The vector or field-oriented control with sensorless estimation will be increasingly popular as the industry standard with the obsolescence of scalar control.

The direct torque control has considerably improved in recent years with the drive performance approaching that of vector control. The complex MPC control is also viable with many sophistications demonstrated in the recent literature but has not yet demonstrated its performance superiority over vector control. Artificial intelligence (AI) techniques will be increasingly used, particularly for fault diagnostics and fault-tolerant control. The literature on motor drives is now diminishing, with current trends in favor of smart grid and RESs. Power electronics is now considered as an integral part of power engineering.

The future trends of motor drives can be summarized as:

- Voltage source converter drives will be universal in the future.
- Cage-type induction motor drives will remain common for general industrial applications.
- Slip power recovery drives will be increasingly obsolete in the future.
- IPM-SM drives will be increasingly popular, particularly for extended speed EV-type applications.
- For high-power applications, WFSM drives will be used with voltage source inverter-multilevel converters (particularly MMCs).
- Vector control will be universal.
- AI techniques, particularly neural networks, will be used for drive performance improvement, fault diagnostics, and fault-tolerant control.

- There is a trend toward drive system integration, particularly in the lower end of power.
- There is a diminishing trend in drive research with technology saturation.

Power Electronics in Smart Grids and RESs

Power electronics is an indispensable ingredient in modern smart grids and RESs. What is a smart grid? A smart or intelligent power grid is basically a vision of an advanced power grid of tomorrow using state-of-the-art technologies in power systems, power electronics, control systems, computers, communications, information, AI, cyber, and so on that will improve system availability, reliability, power quality, energy efficiency, and security with optimum resource utilization and economical electricity to the consumers. A micro- or minigrid is basically a local power system (ac, dc, or hybrid) that can operate autonomously or be interconnected to a grid. Considering these features, our present power grids have major deficiencies. A smart grid normally integrates large fossil and nuclear power stations, RESs, HVdc systems for economical and efficient long-distance power transmission, FACTS for unified active (P) and reactive power (Q) control in transmission circuits, and STATCOMS for VAR compensation, where most of these elements are heavily based on power electronics.

The segmentation of a large power grid by HVdc and FACTS links improves the stability management of the system. An important function of the smart grid is the supply-demand interactive energy management. If the energy demand curves (always fluctuating) are forced to follow the available generation curve, the energy storage requirement becomes minimal, and the corresponding tariff rate becomes economical. The control and protection of a large smart grid are extremely complex. The power generation has to be scheduled among the different generating units for the demand load curves, and the power flow routing has to be controlled for optimizing system efficiency and reliability, preventing the overloading of any element of the power system. Because of the complexity of operation, the system requires dynamic modeling and real-time simulation based on supercomputers.

Currently, RESs (mainly hydro, wind, and solar) are getting tremendous emphasis all over the world, where the wind and solar PV are mainly based on power electronics. Other renewable sources, such as tidal, wave, geothermal, and biomass, will be explored systematically in the future. The main reasons are that renewables are economical, environmentally clean (green), and distributed all over the world and that they do not have the characteristic disadvantages of nuclear power. Our ultimate goal is to have 100% RESs in the future. Is that possible? It is an ambitious goal with formidable challenges. Currently, about 11% of the global energy in electrical form comes from RESs [2], which is subdivided as follows: hydro, 17%; wind, 15%; solar, 7%; and geothermal, 1%, with the remaining 60% coming from biomass.

The energy potential from wind and solar is tremendous. According to a Stanford University estimate [2], exploring only about 20% of the available wind energy (the European Wind Energy Association estimate is 10%) can meet all the energy needs of the world. Solar energy is distributed all over the world. The solar PV cell cost is decreasing drastically in recent years. Wind or solar, or both together, can easily meet the 100% renewable goal of the world, but the main challenges are:

1) The sources are sporadic in nature, and individual plant capacity is small compared to fossil/nuclear plants. Bulk energy storage (usually by battery) (power electronics-based) requirements makes it expensive. Large offshore wind farms (now being emphasized in the United States) are expensive but have a consistent availability, requiring reduced storage need. Regulating frequency and voltage in a large grid with small power plants is not easy. Extensive research is needed on batteries for economical bulk energy storage.
2) The availability of renewable energy is regional, and it is not difficult to make 100% RESs regionally (for example, Iceland has nearly 100% RESs). However, for 100% RESs in the world, energy has to be transmitted economically and efficiently to the remote corners of the world, which may be challenging. The concept technology of the

MY EXPERIENCE IN THE UNIVERSITY OF TENNESSEE (1987–2021)

I decided to return to my university career in 1987 after spending 11 years at GE-CRD. In parallel, I also started working as the chief scientist of the newly established Power Electronics Applications Center at the Electric Power Research Institute. At the end of my GE career, I gained tremendous visibility in the world. Fortunately, a large number of brilliant visiting professors and graduate students from abroad came to work with me with the financial support of their respective governments. Many of them wanted to work in the emerging AI applications in power electronics.

At the University of Tennessee (UT), my projects included: soft-switched power conversion for ac motor drives; high-frequency nonresonant link power conversion; fuzzy-controlled wind generation systems with efficiency optimization control; converter fault studies; neural network-based control and estimation of converters; high temperature superconductivity-synchronous motor ship propulsion with a multilevel converter; and so on. In this period (1987–2021), I wrote/edited six more books in power electronics, and I guest edited two special issues of *Proceedings of the IEEE*. I got the opportunity to travel abroad extensively to give tutorials, invited seminars, and keynote addresses. The UT provided me office facilities after my official retirement in 2003.

global supergrid is already there, but the cost will be prohibitive.

3) Global energy consumption is increasing steadily with the rise of population and the urge of a higher living standard. The global grid has to accommodate this increasing energy demand for the future.
4) The proposed smart grid technology has to be extended to the global grid so that energy is economical for consumers with optimum resource utilization, reliability, power quality, energy efficiency, and security.
5) Linking countries across the world in such a global grid may be a formidable political problem. Despite these challenges, it is the author's belief that the world will eventually see 100% RESs, ousting the well-established fossil and nuclear power plants.

Power Electronics in Solving Climate Change Problems

Power electronics plays a significant role in solving climate change problems [5]–[7], which are such serious concerns in our society. Climate change or global warming is primarily caused by burning fossil fuels (coal, oil, and gas), which generate greenhouse gases (mainly CO_2) and trap the solar heat that raises the atmospheric temperature gradually. The harmful effects of climate change are the melting of polar ice caps and glaciers around the world; severe droughts in tropical countries near the equator; more hurricanes, tornados, rains, and floods; the increased acidity and temperature rise of sea water; the deterioration of fresh water supply; and the spread of tropical diseases. Solving climate change problems remains a challenge in the 21st century. The obvious solution of the problem is the economization of our energy consumption and replacing fossil fuel-based energy generation by RES-based clean energy (which uses power electronics). One way to promote the RESs is the implementation of a carbon tax.

Energy saving is one of the important goals in power electronics applications. Around 65% of generated energy in the United States is consumed in motor drives, and 20% is used in lighting. About 75% of the drives are used in pumps, fans, and compressor-type drives. In this class, variable-frequency drives can save nearly 30% of energy. If LED lamps are used instead of fluorescent or traditional incandescent lamps, a substantial amount of energy can be saved. Similarly, variable-speed air-conditioners/heat pumps can save up to 30% energy. Of course, energy needs for home or space heating can be substantially reduced by proper insulation. Electric transportation, including EVs, can eliminate pollution if the energy is generated by RESs.

Considering the present trend, it can be predicted that the world will eventually have 100% EVs, eliminating internal combustion engine vehicles and HEVs. Promoting mass electric transportation, such as in Japan, can save a lot of energy. A considerable amount of energy can be saved by improving the efficiency of generation, transmission, and utilization by using the smart grid technology in the future. Unfortunately, a significant amount of energy is wasted in affluent countries like the United States because it is cheap and because of bad consumer habits. In the author's opinion, widespread energy efficiency improvement by power electronics and other methods with existing technologies can save around 20% of global energy consumption, and another 15% can be saved by the rigorous control of energy waste [2], [6]. Finally, global climate change problems are solvable by the united effort of the humanity.

Summary

In this article, the author has attempted to give a brief but comprehensive review of power electronics technology and his vision of the future progression, based on his knowledge and experience. The power semiconductor devices, converter circuits, and motor drive areas have been covered in the article. Some emphasis has been given on devices because of their importance and dynamic advances in power electronics evolution. A brief review of classical power electronics was included in the beginning for completeness. The areas of smart grids and RESs along with climate change problems have also been included because of the impact of power electronics in these important areas. Since the author has pursued the power electronics field very aggressively during his long career in both the industrial and academic environments, a brief sketch of his career experience has been inserted within the contents of the article. Finally, in conclusion, I would like to mention that the dedicated and relentless contributions of so many scientists and engineers have made the power electronics technology so rich today.

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