The IGBT Compendium:

Applications and Social Impact

By

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# The Insulated Gate Bipolar Transistor

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Abstract

Today, the IGBT is pervasively used in the consumer, industrial, lighting, medical, transportation, air-craft, financial, and renewable power generation sectors of the economy resulting in enhanced comfort, convenience, and quality of life for billions of people from around the world. The cumulative impact of the improved efficiency of IGBT-enabled applications has been a cumulative cost savings of $2.7 Trillion for U.S. consumers and $15.8 Trillion for World-wide consumers over the last 20 years. At the same time, the improved efficiency produced by IGBT-enabled applications has produced a cumulative reduction in carbon dioxide emissions by 35 Trillion pounds in the United States and 78 Trillion pounds World-wide during the last 20 years. The IGBT has therefore already had a major impact on creating a sustainable world-wide society with improved living standards while mitigating the environmental impact.

The IGBT is now being used in electric and hybrid-electric vehicles made by all manufacturers for delivery and control of power to the motors. This will continue to have a huge impact on the ability of our society to migrate away from gasoline consumption in the future. In addition, the IGBT is an essential technology required for conversion of solar and wind power to the well regulated electric power that must be delivered to consumers and the industry. It will therefore have a major impact on the ability of our society to migrate from fossil fuels (coal, natural gas) to renewable energy sources (solar and wind) in the future.
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1 Introduction

Today, the IGBT is pervasively used in power electronic systems and their applications to improve the comfort and quality of life for billions of people from around the world. The impact of the IGBT on society can be measured by asking the question: “What would happen if all the IGBT were removed from the applications that they serve today?” The answer is quite revealing:

(a) Our gasoline power cars would stop running because the electronic ignition systems would no longer function;
(b) Our hybrid electric and electric cars would stop running because the inverters used to deliver power from the batteries to the motors would no longer function;
(c) Our electric mass-transit systems would come to a standstill because the inverters used to deliver power from the power-grid to the motors would no longer function;
(d) Our air-conditioning systems in homes and offices would stop working because the inverters used to deliver power from the utility company to the heat-pumps and compressors would no longer function;
(e) Our refrigerators and vending machines would no longer function making the delivery and storage of perishable products impossible;
(f) Our factories would come to a grinding halt because the numerical controls use to run the robots would cease to function;
(g) Our new low-energy compact fluorescent bulbs would stop functioning limiting our activities to the daytime;
(h) Our portable defibrillators recently deployed in emergency vehicles, on-board airplanes, and in office buildings would no longer be operational putting over 100,000 people at the risk of death from cardiac failure;
(i) Our new solar and wind based renewable energy sources would not be able to deliver power to the grid because the inverters would stop functioning.

In conclusion, the quality of life in our society would be greatly impaired if the IGBT is no longer available.

In September 2005, when celebrating their 30th anniversary of covering trends in power semiconductor technology, Power Electronics Technology magazine published a review article with the milestone chart reproduced in Fig. 1. The first discrete power transistors evolved in the 1950s from the invention of the bipolar transistor by Brattain, Bardeen, and Shockley in 1947 for which they received the Nobel Prize in 1956. Soon thereafter, the integrated circuit was conceived by Robert Noyce and Jack Kilby, who received a Nobel Prize in 2000. During the 1950s, power thyristors were also commercially introduced for high power applications (not shown on the chart). Major manufacturers for the bipolar devices were General Electric and Westinghouse Corporation. The next major innovation in power devices was the introduction of the power MOSFETs by Siliconix in 1975 and International Rectifier in 1978. The power semiconductor industry was bifurcated into two tracks with one group of companies producing bipolar power devices and a separate group of companies producing power MOSFET devices. At that time, the manufacturing of these devices was considered to be incompatible because the MOS devices required know-how in control of semiconductor surface properties while the
bipolar devices relied on control of minority carriers within the bulk regions of semiconductors.

In 1979, I proposed the functional integration of MOS and bipolar physics within the same monolithic structure. This led to my invention of the IGBT in 1979-1980 as indicated in the chart. In December 2010, I was inducted into the Electronic Design Engineering Hall of Fame for the invention, development, and commercialization of the Insulated Gate Bipolar Transistor (IGBT), joining well known luminaries (e.g. Edison, Tesla, Marconi, Kilby, Noyce, etc) in the electronics field. The award announcement states: “While working at General Electric in the late 1970s, Baliga conceived the idea of a functional integration of MOS technology and bipolar physics that directly led to the IGBT’s development... it remains undeniable that Baliga’s vision and leadership played a critical role in moving the IGBT from a paper-based concept to a viable product with many practical applications.”
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The Insulated Gate Bipolar Transistor (IGBT) mode of operation was first discovered by me in 1978 while working at the GE Corporate Research and Development Center and reported in the literature in 1979\(^2\) where the device structure was described as a power MOSFET structure with an anode region. In this paper, it was demonstrated that MOS-gate controlled current saturation was possible in a 4-layer semiconductor device structure demonstrating operation without regenerative action. Prior to this discovery, it was believed that a 4-layer semiconductor device would latch-up due to internal regenerative action once current flow was initiated by the gate bias resulting in loss of gate control. Shortly after my discovery of the IGBT-mode, my analysis indicated that it was possible to obtain high on-state current density in devices designed for high voltage operation. This formed the basis of my invention disclosure letter at GE which led to a U.S. patent application filed on December 2, 1980\(^3\). This patent includes not only the well-known IGBT structure but novel structures that utilize tunneling of current from the emitter contact metal and the gate-bias induced channel inversion layer.

Immediately upon my conception of the IGBT structure, it was obvious to GE that this device had wide spread applications within many business units of the company. The projected impact across GE was so large that it prompted a personal visit by the Chairman, Jack Welch, to GE-CRD for a briefing by me. Impressed by the business opportunities created by the IGBT for GE, Dr. Welch placed an immediate embargo on any publications while we focused on bring the technology to the market within many applications. The applications targeted were adjustable speed motor drives for use in air-conditioning (heat pumps) for homes and offices, small appliances such as steam irons and space heaters, large appliances such as refrigerators and washing machines, advanced high-efficiency lighting, drives for electric locomotives, numerical controls for factory automation, and even medical systems such as CAT scanners. The publication embargo was lifted when the GE Semiconductor Products Division submitted a paper in September 1982 for presentation at the 1983 IEEE Industrial Applications Society Meeting\(^4\) and subsequently received a 1983 ‘Product of the Year Award’ from Electronics Products magazine. With lifting of the embargo in September 1982, I was able to publish the first paper on the IGBT device structure and operating physics at the IEEE International Electron Device Meeting in December 1982\(^5\).

It is commonplace for any innovation made at the research laboratory, with substantially improved performance over existing products, to require a new manufacturing process that requires installation of an expensive new production facility. Fortunately, I was able to engineer the IGBT structure so that it could be manufactured in an existing production line for power MOSFET products. Consequently, I was able to create a mask design and process flow to allow fabrication of the first IGBT devices in 1981 at GE’s recently acquired Intersil facility in California under the supervision of Nathan Zommer. This resulted in the availability of high performance IGBT devices with high yield and uniformity within a remarkably short time frame of less than 6 months after its conception.

When I first reported the idea for the IGBT, skeptics concluded that it was not a viable technology because the internal 4-layer structure would latch-up leading to destructive failure and because the known lifetime control processes could not be applied to the device resulting in very low switching speed that would severely limit its applications. Fortunately, I was able to
overcome both of these show-stoppers. I overcame the latch-up problem by incorporation of a deep P⁺ diffusion into the basic D-MOS structure. In addition, I was able to create an electron irradiation process for controlling the lifetime in power MOSFET devices for utilization in controlling the switching speed of IGBTs. Prior to this work, it was believed that the electron irradiation process could not be used for MOS-gated devices due to an observed large shift in the threshold voltage because of damage produced within the gate oxide. I discovered post-irradiation annealing conditions that enabled removal of the damage to the gate oxide while preserving the desired lifetime reduction within the silicon. When the first IGBTs became available off the production line, I was able to utilize this lifetime control process to make the first devices with switching speed that could be tailored for applications ranging from 60-Hz for offline appliance controls to 10-kHz for adjustable speed motor drives to 100-kHz for uninterruptible power supplies.

With the availability of fast switching IGBTs, GE was able to release a 5-hp “Smart Switch” adjustable speed motor device product for use in air-conditioners (heat-pumps) made by Carrier and Trane creating a new GE business unit. Subsequently, I designed a p-channel IGBT structure and fabrication process to enable release of the “Genius I/O” product in 1986. This product for numerical controls (robotics) catapulted GE to among the top factory automation companies leading to the winning bid for the first GM Saturn car manufacturing facility. In addition, my measurements confirmed high temperature operability of the IGBT making them highly suitable for application in adverse environments such as under the hood in automobiles, in the base of lamps, and even inside steam irons.

Under my supervision at GE-CRD, an intensive effort was undertaken in the 1981-1985 period to find methods for suppressing the latch-up of the parasitic thyristor within the IGBT structure. In addition to the addition of a deep P⁺ region as previously mentioned, the latch-up current density was increased by (a) reduction of the gate oxide thickness and (b) using innovative cell layout topologies. This effort created the foundation of rugged IGBT structures that could be utilized in applications without snubber circuits. Since 1985, world-wide interest in IGBT has grown exponentially with many publications regarding enhancing the performance of IGBTs and extending their voltage and current ratings. A description of these technologies can be found in my recently published textbook on power devices. Today, IGBT modules are available with the capability of handling over 1000-amperes and sustaining more than 5000-volts.

### 2 Power Semiconductor Device Applications

The applications for power devices can be classified in two domains. In the first case, the applications can be displayed based up on the current and voltage ratings for the power devices as shown in Fig. 2 using a logarithmic scale for both axes due to the very large range of the ratings. It can be seen that the IGBT applications that lie in the green area extend between current ratings of 1 to 1000- amperes and voltage ratings from 200 to 6000-volts. Although there are a multitude of applications for the IGBT as discussed later, three prime examples that are
having a large impact on society are high-lighted in the figure. They are (a) IGBT-based electronic ignition systems for gasoline powered cars and trucks, (b) IGBT-based adjustable speed motor drives for air-conditioning and refrigeration, (c) IGBT-based drives for electric trains such as the Shinkansen bullet train used in mass-transit, and (d) IGBT-based compact fluorescent lamps for domestic and industrial lighting applications. Recently, the application for IGBTs has been extended to plasma displays (TVs) due to their high current handling capability. In addition, as its power ratings are enhanced with progress in increasing its current and voltage handling capability, the IGBT is finding applications in power transmission systems. All renewable energy sources, such as solar-power and wind-power, require conversion of the generated electricity to well-regulated 60-Hz power that be delivered to the power grid. This is performed using IGBT-based inverters.

Fig. 2: Applications for Power Devices based up on their Current and Voltage Ratings.

The applications for power devices can also be examined on the basis of the frequency of operation as displayed in Fig. 3. In this figure, the operating frequency of various applications ranges from 60-Hz at the low end to 1-Ghz on the high end. It can be observed that the power requirements scale inversely with increasing frequency. At the lower end of the frequency spectrum, very high power levels of Megawatts are encountered in power distribution and mass...
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transit applications. On the other extreme, the power level reduces to about 100 watts at frequencies above 100-MHz. IGBTs are uniquely well-suited for applications that operate between 60-Hz and 100-kHz. During initial stages of development, the IGBT applications were constrained to power levels of 100-kW but progress with building power modules has enable enhancing their power handling capability to over 5 Megawatts. Consequently, IGBTs are now being applied to mass-transit systems, such as the Shinkansen bullet train\textsuperscript{18}, and power distribution systems\textsuperscript{19}. Recently, the operating frequency for high power IGBTs has been extended by fabrication of devices from silicon carbide. Silicon carbide is a wide band gap semiconductor material with superior breakdown field strength that allows improving the operating frequency of IGBTs by an order of magnitude\textsuperscript{20}.

![System Power Rating (Volt-Amperes)](image)

Fig. 3: Applications for Power Devices based up on their Frequency Capability.
3 IGBT Structure and Operation

The IGBT structure and its operating principles have been described in detail in my textbook\textsuperscript{21}. Two basic structures for the IGBT have evolved into products. The basic IGBT structures are shown in Fig. 4 together with its circuit symbol. The D-MOS IGBT structure was the first structure used to demonstrate the superior performance of the IGBT for high voltage operation\textsuperscript{4}. The U-MOS IGBT was developed shortly thereafter to reduce the on-state voltage drop\textsuperscript{22}. In both devices, the device structure contains a wide-base P-N-P transistor (that is designed to support the forward and reverse blocking voltage) monolithically integrated with a MOSFET for providing its base drive current. The symmetric IGBT structures optimized for AC power circuits, shown in Fig. 3, are capable of supporting high forward and reverse voltages\textsuperscript{4}. Asymmetric IGBT structures\textsuperscript{23} that are optimized for DC power circuits are illustrated in Fig. 5 together with its circuit symbol.

In the on-state, the IGBT operates with very strong injection of minority carriers into the lightly doped N-drift region. This produces a reduction of the resistance of the N-drift region by many orders of magnitude allowing the structure to operate at high on-state current densities with low on-state voltage drop. The power handling capability of the IGBT structure is consequently an order of magnitude larger than for high voltage power MOSFET structures. Consequently, the IGBT structure provides the desired high input impedance feature of the power MOSFET, which makes its control circuit inexpensive, with high power handling capability that is desirable for medium and high power applications. The availability of the IGBT improved the power gain (ratio of output to input power) by more than a million-fold. The IGBT structure has been demonstrated to be extremely rugged eliminating the need for expensive and lossy snubber.
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circuits that were previously necessary with bipolar devices. These features have allowed a very rapid growth in the current and voltage ratings of IGBT devices. The growth in the power handling capability of IGBTs is illustrated in Fig. 6. These power ratings are sufficient for serving all the IGBT applications discussed in the previous section including traction (electric trains) and power distribution applications.
4 IGBT Applications

The applications for IGBTs have been continually expanding since its conception in the early 1980s. It has already had a large impact on: (a) the Transportation sector; (b) the Lighting sector; (c) the Consumer sector; (d) Factory Automation sector; (e) the Industrial sector; (f) Publishing sector; (g) the Medical sector; (h) the Aerospace sector; (i) the Marine sector; (j) the Defense sector; (k) the Aerospace sector; (l) the Financial sector; (m) Power Transmission and Distribution sector; (n) Fossil-Fuel Power Generation sector; (o) Renewable Energy Power Generation sector; (p) Mass Energy Storage sector; as well as (q) many other sectors of the economy. In this section, the applications for IGBTs in the various sectors of our economy will be described with specific examples of circuits containing IGBTs that meet the needs of the applications. In all cases, extensive references from the technical literature are provided to document the utilization of IGBTs and the benefits derived from these devices.

4.1 Gasoline Powered Vehicles

At present, gasoline power cars and trucks still comprise the majority of vehicles used in our society for commuting, recreation, shopping, and transportation of merchandise. Until the late 1980s, the ignition system for the internal combustion engine used in gasoline powered vehicles was based up on using a mechanical distributor developed by Charles Kettering, as shown in Fig. 7, for controlling the timing for the spark plugs. This method was prone to poor control and failure from wear out of the contacts. The availability of the IGBT enabled introduction of reliable distributor-less electronic ignition systems in the late 1980s with no moving parts.24 The article states: “A primary constraint to the adoption of electronics innovations was the ability to make components durable enough to withstand the heat and vibration factors of an automobile
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in daily use”. The IGBT was the first power switch with sufficient high temperature operation and ruggedness attributes to allow cost effective and reliable implementation of the distributor-less electronic ignition system.

The basic circuit for the electronic ignition system is illustrated in Fig. 8. The IGBT is used as the switch on the primary side of the transformer due to the high voltages encountered in this application. Many companies sell IGBTs specifically designed for use in the electronic ignition systems. These IGBTs include gate-emitter ESD protection and temperature compensated gate-collector voltage clamps. The electronic ignition systems market represents one of the fastest growth opportunities for IGBTs. By the end of 2000, just one power semiconductor company, INTERSIL, had already shipped more than 50-million ignition IGBTs for this market.

It is generally acknowledged that the distributor-less electronic ignition system reduces maintenance costs while allowing more precise control of the timing for the spark plugs which improves fuel efficiency, reduces emissions, and increases the overall power of a car. Electronic ignition systems have the advantage of operating at a higher voltage than possible with mechanic points. The larger voltage can be applied across a wider spark gap leading to a longer and broader spark. The larger spark volume allows a leaner fuel mixture that leads to better fuel efficiency and a smooth running engine. The improvements in fuel efficiency derived from using the electronic ignition systems has been documented to range from 2 to 4 miles per gallon of fuel. A UNDP study on the impact of electronic ignition systems has established a 10 percent improvement in fuel economy while reducing environmental pollution. Based up on the available data, it is reasonable to assume that the introduction of the electronic ignition system using IGBTs has produced fuel savings of at least 10 percent.
Two-thirds of the electricity in the U.S. is used to operate motor driven equipment. The common applications in the residential and commercial sectors are for air-conditioning and refrigeration. In the industrial sector, motors are extensively utilized for process control with pumps. Other applications for motors include irrigation, waste water treatment, elevators, conveyor belts, etc. Most applications utilize induction motors due to their simple, low-cost construction with highly reliable operation for long periods of time. Induction motors operated a fixed rotational frequency (rpm) that is a multiple of the AC frequency of the input power supplied to its windings. The control of any process operated using the motor must be accomplished by using dampers as illustrated in Fig. 9. The damper regulates the output by converting the rest of the power delivered by the motor into wasted heat. Consequently, although the induction motor operates at 95% efficiency, most motor controlled processes operate with efficiencies below 50 percent.

The adjustable speed drives (ASDs), also referred to as the Variable Speed Drives (VSDs) and Variable Frequency Drives (VFDs), are based up on controlling the output speed of
motors by supplying them with a variable frequency input power. This requires conversion of the 60-Hz (or 50-Hz in some countries) AC power supplied by the utilities into variable frequency power ranging from 60-Hz to over 10-kHz as illustrated in Fig. 10. The operating efficiency of the adjustable speed drive depends up on the efficiency of the inverter stage that is used to convert the input 60-Hz power to the variable frequency output power. Adjustable speed drives were transformed into an affordable and dependable technology after the availability of the IGBTs. In fact, the first application for IGBTs that I worked on at the GE research center in 1982 was adjustable speed drives for use in heat-pumps for air-conditioning. This work was described by me at a Motor Drives Conference in October 1983. Since that time, adjustable speed drives have been widely utilized to improve the efficiency in residential and commercial sectors. The applications for adjustable speed motor drives include: (a) Light and Medium Industry such as auto part assembly, food production, semiconductor manufacturing, and light machining; (b) Process Industry such as pulp and paper mills, chemical plants, oil refineries, and steel mills; (c) Heavy Industries such as mining, oil and gas production, and power plants; (d) Water and Wastewater such as municipal water and wastewater plants, and irrigation; (e) Commercial HVAC such as heating and cooling of commercial buildings; and (f) Agricultural Industries such as farms for irrigation and product processing.

Variable frequency drive technology has been extensively discussed in many books. The most commonly used circuit topology is shown in Fig. 11. It consists of an input rectifier stage to convert the fixed frequency input power to a DC source. The variable frequency output power fed to the three-phase motor windings is then synthesized using an inverter stage containing IGBTs and fly-back rectifiers. The high power handling capability of the IGBT with snubberless operation enabled the development of compact, low-cost, and reliable adjustable speed motor drives. A large number of publications have described the use of adjustable speed drives based up on IGBTs in the literature. In tracing the history of motor drive technology, Sawa and Kume state: "Variable speed motor drives require power electronics and it can be said that this work has contributed to the prosperity of today’s world-wide..."
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economy and allows people to enjoy a more complete social life. ... The voltage source type PWM control IGBT inverters with 15-kHz carrier frequency was produced in 1990. ... After this IGBTs were widely used and became the standard power devices for general purpose inverters. This continues to this day.” The significant reduction (more than 10-times) in the complexity, size and weight of adjustable speed drives derived after the availability of the IGBT has been documented\cite{47}. Blaabjerg and Thoegersen state: “Presently, the Voltage Source Inverter architecture with six diodes and six IGBTs is totally dominant for Industrial Drives in the power range from 0.5 to 500 kW.” They project a 10% annual growth in the market for these adjustable speed drives. The benefits of IGBT-based inverters in adjustable speed drives for the cement and minerals industry have also been described\cite{48}.

4.3 Electronic Ballasts for Compact Fluorescent Lamps

According to the U.S. Department of Energy, artificial lighting consumes about 10% of household electricity use. Most residential lighting in the U.S. continues to depend up on the use of incandescent lamps, first commercialized by Edison in 1879, that utilize a tungsten filament to convert electricity into light. A typical A-line incandescent lamp used in homes is shown in Fig. 12(a). Unfortunately, only 4 percent of the electricity is converted to light in an incandescent lamp with the remaining 96% lost as heat into the environment. The low efficiency of the incandescent lamps has motivated the development of alternate technologies. In order to be attractive to consumers, it is important that any replacement for the incandescent lamp should have the same form factor and be compatible with existing lamp sockets in homes. One of the major problems with this requirement is that the electronics required to control the gas discharge processes in fluorescent lamps must fit in the small space at the base of the lamp and be tolerant to the high temperature produced by proximity to the gas discharge. The IGBT was the first power semiconductor device with the compact form factor suitable for this application due to its high power handling capability per unit area. In addition, the high input impedance of the MOS-gate structure of the IGBT enabled integration of the control circuit allowing drastic reduction in the volume of the electronics. Furthermore, it was demonstrated by me in 1983 (published in 1985\cite{12}) that the IGBT was capable of operating at high ambient temperatures with low on-state and switching losses. At GE, the impact of the availability of the IGBT on the lighting business was immediately apparent. A compact fluorescent lamp was developed under the TRIAD program by end of 1984\cite{49}. However, market introduction of this product was postponed by the lighting division under the belief that consumers could not be convinced of the economic benefits of energy savings accrued from the new lamp technology. This decision was rescinded many years ago and GE now markets these lamps under ‘GE Energy Smart Compact Fluorescent (CFL) Bulbs’\cite{50}.

A typical compact fluorescent lamp that is now commonly available in stores is shown in Fig. 12(b) together with the electronics inside the base. Compact fluorescent lamps have been demonstrated to reduce energy consumption by 80 percent while operating for 10-times the life-span of incandescent lamps. The circuit diagram for the IGBT-based (MMG05N60E) ballast
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used in a typical residential compact fluorescent lamp is provided in Fig. 13. This circuit can also
be used for other fluorescent lamps used in industrial settings. In the Motorola (On-
Semiconductor) application note, it is demonstrated that the IGBT offers the most cost effective
power device technology for use in the electronic ballast of CFLs when compared with bipolar
power transistors and power MOSFETs.

Fig. 12: (a) Incandescent lamp; (b) Compact Fluorescent Lamp based on using IGBT ballast.

Fig. 13: Circuit Diagram for the IGBT-based Ballast for the Compact Fluorescent Lamp.
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The circuit in Fig. 13 performs the functions of (a) pre-heating the filaments to improve start-up efficiency, (b) striking the fluorescent tube, and (c) continuous operation while the lamp is on. The typical frequency of operation is 30 kHz while the lamp is turned-on. The application note\textsuperscript{51} states: "With a current capability of 500 mA in steady state, up to 2A in pulse mode, the MMG05N60E (IGBT) is well suited for the full power range of CFL applications. ... since the power into a fluorescent tube is a function of its length, the current flowing into the transistors is almost constant over the 7 W to 23 W range." The Motorola MMG05N60E IGBT has a fly-back diode integrated into its structure and is capable of operating up to $+100^\circ$C ambient temperature. The article concludes by stating: “The IGBT meets all the electrical requirements for a Compact Fluorescent Lamp application. Thanks to its chip size, it can be packaged in either an SOT223 or a more conventional TO92. This brings significant cost savings, compared with other semiconductor technologies, without downgrading the global performance of the circuit. Because it is a MOS-gated device, it can be driven by standard MOS drivers, allowing the design of high-end modules with built-in functions like dimming or remote control, functions not easily achievable with a bipolar transistor.” These IGBTs are available under the PowerLux IGBT brand from Motorola (ON-Semiconductor).

Many companies have developed optimized IGBT products specifically for the lamp ballast applications due to the large market. One example is the “LightMOS” IGBT product available from Infineon\textsuperscript{52}. In this device structure, a reverse conducting diode has been integrated into the IGBT structure\textsuperscript{53}. The author’s state: “Summarizing, the LightMOS offers an excellent price performance ratio for this (lamp ballast) extreme cost sensitive segment of applications.”

4.4 Transportation Sector

The IGBT has had a major impact on the transportation sector of the economy in the United States and arguable even more around the rest of the world. As previously discussed in section 4.1, the IGBT enabled the introduction of cost effective and reliable electronic ignitions systems that have improved gasoline fuel efficiency by at least 10 percent. They have also been critical elements in the improvement of mass transit systems and the deployment of electric and hybrid-electric vehicles as discussed in this section.

4.4.1 Motor Drives for High Speed Rail

Millions of people from around the world rely up on using mass transit systems for their daily commute to work. Modern mass transit systems rely up on electric trains where the propulsion is derived from supplying AC power to motors. In addition to urban transportation systems, electric trains have become commonplace for travel between cities in Europe and Asia. High speed rail, such as the European TGV and the Japanese Shinkansen bullet trains shown in Fig. 14, allows travel by large numbers of people while avoiding fossil fuel consumption experienced with gasoline powered automobiles and aircraft.
Until the 1990s, the silicon GTO (Gate Turn-Off Thyristor) was the only available power semiconductor switching device with the power handling capability suitable for this application. In the 1990s, the ratings of IGBTs had sufficiently advanced, as illustrated in Fig. 6, to exceed one Mega-Watt allowing penetration of the IGBT into this traction market. The availability of the IGBT allowed significant improvements in the motor drive technology due to elimination of snubber circuits and an increase in the operating frequency of the inverter circuit used to deliver power to the motors\textsuperscript{54}. ALSTHOM in Europe claims to be the first company to introduce IGBT traction systems to the rail industry. Their ONIX traction systems allow a 50\% reduction in volume, a 30\% reduction in weight, a 33\% improvement in lifecycle costs, and a reliability improvement by 50\% over the previous generation (GTO-based) traction systems\textsuperscript{55}. Central Japan Railway and West Japan Railway have collaborated on the development of a Series 700 bullet train using IGBT-based traction system\textsuperscript{56}. The authors state: “The Series 700 aims to realize better riding comfort, environmental friendliness, easy maintenance work, and low manufacturing cost. ... Due to improved waveform, the traction transformers are drastically reduced. ... As a result of the IGBT, great effect of reduction of interior noise and higher harmonics was assured. ... heat-loss by the harmonic current was remarkably reduced. Because of low heat-loss design, light and compact traction system was realized. ... In terms of cost reduction, this IGBT traction system also gives an advantage. IGBT do not need large power supply to drive and the IGBT system is composed of simpler parts, compared to the GTO systems. Therefore, total cost of the IGBT system was reduced. ... Thus, IGBT applied innovative traction systems of the series 700 realized higher level of quality, interior noise reduction, light and compact total systems, low cost and easy maintenance.”

IGBTs have even penetrated the traction market in developing countries. The Indian Railways has deployed IGBT-based drives in 2,415 trains (see Fig. 15) in the Central Railway and Western Railway zones\textsuperscript{57}. The article states: “The IGBT technology will help us save up to 30 percent of the energy required to run a train by converting the kinetic energy that is lost in braking into reusable electrical energy. ... This is expected to save the railways Rs 200 crore (\$50 Million) annually on energy expenses.” With more than 4,000 miles of high speed lines under
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construction in China, China’s Ministry of Railways has already placed orders for 280 high speed train-sets (see Fig. 15) operating at 200 to 250 km/hr\(^2\). The CRH3 high speed trains deployed in China are based up on Siemens Valero high speed train platform that utilizes IGBT-based motor drives. The Valero went into service for the 2008 Olympic Games. At a speed of 350 km/h, these trains have reduced the travel time from Beijing to Shanghai to about 4 hours\(^5\). IGBT-based traction technology has dominated high speed rail deployment in China since 2007\(^6\). The development of IGBT-based traction systems, and their successful marketing and delivery around the world has been proudly documented by many companies. Bombardier Transportation claims the ‘World’s first application of IGBT power converters (Adtranz 12X) in a locomotive in 1997’ followed by sales in China (HXD3B) and North America (ECO4 MITRAC)\(^6\). Toshiba Transportation Systems\(^6\) has been supplying IGBT VVVF inverters since 1996 to South Korea (SMG Line Nos. 7 and 8), Egypt (Cairo Metro Line 2), Indonesia (PT-INKA), Chicago (NICTD), Ireland (IE), Venezuela (Caracas Urban Railway), USA (JFK Air-Tain), Canada (Vancouver Sky-Train), Philippines (Manila No. 2 Line Light Rail Transit), Taiwan (Taiwan Railway Authority), and Brazil.

![Chinese High Speed Train](image1)

![Indian Railways Train](image2)

**Fig. 15:** (a) Chinese High Speed Train; (b) Indian Railways Train.

**4.4.2 Motor Drives for Electric and Hybrid-Electric Vehicles**

It is well recognized that gasoline power vehicles produce significant urban pollution while consuming a dwindling fossil fuel resource. A solution to this problem is the deployment of electric and hybrid-electric vehicles. The development of vehicles powered from electricity has a long history extending to the 19\(^{th}\) century. The first commercial application of electric cars was in 1897 as a fleet of electrical New York City taxis, built by the Electric Carriage and Wagon Company of Philadelphia. Subsequently, electric cars were produced in the US by Anthony Electric, Baker, Columbia, Anderson, Edison, Fritchele, Studebaker, Riker, Milburn, and others during the early 20th century\(^6\). Due to limitations in the range and poor reliability of batteries, electric vehicles fell out of favor until the 1990s. With increased acknowledgement of vulnerable gasoline supply from the middle-east and the impact on urban health due to pollution from gasoline powered cars, the hybrid-electric car has taken a foothold in the automobile market.
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Even from the early 1990’s it was apparent that the IGBT is the ideal power switch for motor drives in electric vehicles\textsuperscript{64,65}. The most successful electric car in the marketplace has been the Toyota Prius shown in Fig. 16 with its IGBT motor drive module. All hybrid-electric and electric cars that have been subsequently introduced into the market have relied up on IGBT-based motor drives. In addition, the regenerative braking capability, that has a big impact on the efficiency of hybrid-electric cars, relies up on IGBTs.

![Prius Hybrid-Electric Car](image1)

![IGBT Motor Drive](image2)

**Fig. 16:** (a) Prius Hybrid-Electric Car; (b) IGBT Motor Drive.

![Modes of Operation](image3)

**Fig. 17:** Modes of Operation for an Electric Car.

The various operating modes\textsuperscript{66} for a hybrid-electric vehicle are illustrated in Fig. 17. At low speed typical of commuting within cities, the hybrid-electric car operates with only power delivered from the battery as shown in Fig. 17(a). The conversion of the available DC power from the battery to the desired variable frequency AC power to the electric motor is done using
IGBT-based inverters. When the hybrid-electric car is operated on highways, it operates with power delivered from both the gasoline-powered internal combustion engine (ICE) and the battery-powered electric motor as illustrated in Fig. 17(b). In this case, IGBTs are needed to operate the ignition system of the ICE and to drive the motor. The battery in the hybrid-electric car must be recharged to renew the stored energy. This is also performed using IGBT-based circuitry in the power electronics module as indicated in Fig. 17(c). One of the important approaches to achieving high fuel efficiency in a hybrid-electric car is to utilize regenerative braking. This function is also performed using IGBT-based power electronics in the hybrid-electric car as shown in Fig. 17(d). It can be concluded that the IGBT is at the heart of the power delivery system in the hybrid-electric car and essential to achieving the desired high fuel efficiency.

Fig. 17: Toyota Roadmap for Hybrid Electric Vehicles.

Toyota has published its roadmap for power electronics in hybrid-electric vehicles. As shown in Fig. 18, all of its vehicles rely upon utilizing IGBTs in the delivery of power from the battery to the electric motor. Each inverter contains six IGBTs for control of power to the motor as shown in the inset. Intelligent power drive modules based upon IGBTs have been developed for EV/HEV applications by semiconductor manufacturers for this application. The increasing motor power of successive generations of hybrid-electric cars requires an increase in the DC bus voltage from 200-V to 650-V. This requirement has been successfully fulfilled by using IGBTs with higher voltage ratings.

There has also been recent interest in the development of all electric vehicles (EV’s) and plug-in hybrid electric vehicles (PHEV’s), such as the Tesla Roadster and the GM Volt, shown in Fig. 19. In these vehicles, the IGBT-based inverters are essential for delivery of power from the battery to the electric motor in an efficient manner. The IGBT-based power electronics is also required to achieve good fuel efficiency by performing regenerative braking.
Fig. 19: (a) Tesla Electric Car; (b) GM Volt.

Fig. 20: Electric Car Battery Chargers (a) REVAi/G-Wiz in London; (b) GE Charger.

Fig. 21: Toyota Residential Electric Car Battery Charger.
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The success of plug-in electric vehicles will require deployment of battery chargers in residences, at office parking lots, and at charging stations distributed within cities. Examples of battery chargers already deployed in Europe and the United States are shown in Fig. 20. In addition, companies are developing battery chargers, as shown in Fig. 21, which can be installed at the residences of owners of all electric-cars. A typical buck-boost circuit utilizing IGBTs is

Fig. 22: Residential Electric Car External Battery Charger Circuit Diagram.

Fig. 23: On-Board Residential Electric Car Battery Charger Circuit Diagram.

The success of plug-in electric vehicles will require deployment of battery chargers in residences, at office parking lots, and at charging stations distributed within cities. Examples of battery chargers already deployed in Europe and the United States are shown in Fig. 20. In addition, companies are developing battery chargers, as shown in Fig. 21, which can be installed at the residences of owners of all electric-cars. A typical buck-boost circuit utilizing IGBTs is
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shown in Fig. 22 for residential battery chargers of electric vehicles. As an alternative, it is possible to use the IGBT-based inverter and the electric motor in the electric vehicle to create an on-board battery charger\textsuperscript{70} as shown in Fig. 23. In the case of charging stations, it is necessary to perform the battery charging in a much shorter duration than at residences. IGBT-based fast charging topologies have been designed for this application\textsuperscript{71}.

In conclusion, the availability of IGBTs has been crucial to the success the hybrid electric car and to the deployment of the charging infrastructure for the plug-in electric vehicles. The IGBT will continue to play an important role in the availability of cost effective technology for the entire electric vehicle industry.

4.4.3 Motor Drives for Electric Bus and Tram

Mass transit systems within cities must rely upon buses, trams, and underground trains. Many cities have been replacing gasoline powered busses with electric busses and trams to reduce urban pollution. Two examples are shown in Fig. 24. The Ecoride BE35 electric bus made its 2009 debut in major U.S. metropolitan areas including Los Angeles, Sacramento, San Francisco, and San Hose. It can hold up to 37 passengers and can be charged in just 10 minutes. The Tindo (Aboroginal for ‘Sun’) Electric bus has been deployed in Adelaide, Australia, as the first solar-powered electric bus.

Electric transit busses are also being deployed in China. A typical control system for the electric transit bus using IGBTs is shown in Fig. 25\textsuperscript{72}. The drive must be designed to meet the following requirements: (a) wide range of speed including high operating speed; (b) large start-up torque for good acceleration; (c) high efficiency; and (d) regenerative braking to increase utilization of batteries. All of these requirements were met using the IGBT-based motor drive circuit shown in Fig. 25.
Within cities, electric trams have been used for mass transportation from the early 1900s. A lithograph of an early tram is shown in Fig. 26(a). In Europe and Japan, electric tram transit systems have been modernized by using IGBT-based motor drives. According to AEG-Westinghouse Transport Systeme, Germany, the low floor concept is becoming a standard customer prerequisite. This has been enabled by today’s IGBT modules.

4.4.4 Motor Drives for Airport Transit Systems

Airports commonly utilize electric trains for moving passengers between terminals and even into the connecting cities. These electric trains are driven by IGBT-based inverters that have replaced
the GTO-based inverters since 1999. As examples, Toshiba has supplied the IGBT modules for the JFK AirTran and Vancouver SkyTran transit systems shown in Fig. 27.

![Fig. 27: (a) JFK AirTran; (b) Vancouver SkyTran.](image)

### 4.5 Consumer Sector

The quality of life for people in the developed societies has been greatly enhanced by the availability of affordable household appliances. In modern societies, it is taken for granted that every home is equipped with a refrigerator, a washing machine, a microwave oven, and induction cook tops. People in developing countries aspire to increase their living standards until they have similar conveniences. The IGBT is utilized for controlling the power delivery in an efficient and cost effective manner in these appliances. It is also utilized to improve the power factor so that the load on the utilities is reduced.

#### 4.5.1 Refrigerator Compressor Drives

Refrigerators have become essential appliances in society for the preservation of food and beverages. The quality of life for people has been greatly enhanced with the availability of affordable refrigerators for homes. The first widespread use of refrigerators occurred with the introduction of the "Monitor-Top" brand, shown in Fig. 28(a), by General Electric in 1927 with sales of over a million units. The annual sales for modern refrigerators, such as the GE Monogram series shown in Fig. 28(b), have grown to more than 59 million units worldwide by 2003. Most household refrigerators utilize the vapor compression cycle with a circulating refrigerant used to cool the refrigerator compartment. Household refrigerators originally used an on/off controlled, constant-speed, single-phase induction motor to drive the compressor. The poor efficiency of this approach made the refrigerator one of the highest power consumption appliances in the home. In order to improve the efficiency, modern refrigerators with the Energy
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star rating utilize variable-speed, three-phase induction motor drives. Current models that are Energy Star qualified use 50 percent less energy than the average models made in 1974<sup>75</sup>.

![Image of refrigerators](a) (b)

Fig. 28: Home Refrigerators: (a) GE ‘Monitor Top’; (b) GE Monogram.

![Diagram showing the compressor drive system](image)

Fig. 29: Home Refrigerator Compressor Drive.

The basic inverter circuit used for the compressor drive in a refrigerator is shown in Fig. 29<sup>76</sup>. The variable speed drive to the induction motor is provided using the six IGBTs in the inverter stage. The author’s state: “The total energy savings was about 40%. The system is very quiet and maintains a constant temperature within 0.1 °C which improves the quality and shelf life of food stored in the refrigerator.” Many companies have optimized IGBTs for use in
refrigerator compressor drives due to the large market opportunity\textsuperscript{77}. Some companies have developed intelligent power modules, shown in Fig. 30, that combine the IGBTs, fly-back rectifiers, and the drive circuits into a single module\textsuperscript{78}. This provides a very compact and low-cost motor drive option that can be easily adopted for the manufacturing of refrigerators.

4.5.2 Washing Machine Drives

Electric automatic washing machines are now commonplace in homes for the cleaning of daily household laundry. Washing machines were developed to eliminate the drudgery of scrubbing and rubbing to remove dirt from clothes. Electric washing machines were advertised and discussed in newspapers as early as 1904. The first automatic washing machine was introduced by Bendix in 1937 (see image in Fig. 31(a)). Sixty percent of the 25 Million wired homes in the United States had an electric washing machine by 1940. The annual sales for washing machines have grown to more than 58 million units worldwide by 2003\textsuperscript{79}. Many of these units are front loaders as shown in Fig. 31(b). Early automatic washing machines utilized mechanical means for making any changes in impeller/drum speed. Since the 1970s, electronic control of motor speed has become a common feature of most washing machines. Modern automatic washing machines provide many sophisticated features to handle the safe cleaning of a wide range of fabrics with a variety of soil removal requirements. Most modern consumer washing machines have (a) predefined programs for different laundry types; (b) variable temperatures including cold, warm, and hot wash cycles; (c) many fill levels depending up on the load size; (d) many rotation speed settings; and (e) programmable delay of the start of the laundry cycle.

Fig. 30: Intelligent Power Module for Refrigerator Compressor Drives.
The soil removal in an automatic electric washing machine is performed by a process of agitation of the clothes. The agitator is controlled using IGBT-based motor control modules. A typical automatic washing machine control and drive system is illustrated in Fig. 32. The direction of rotation of the motor and its speed can be regulated by using the power delivered via the IGBTs. Inverter control with IGBTs reduces wash/spin noise and vibration, and enables...
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adjustment of the amount of water and motor torque to suit the washing load. EDN magazine\textsuperscript{81} states: “In washing machines eliminating the belt drive and transmission more than pays for the cost of the electronic drive. In addition to the lower price, the machine will have software-defined agitation, use less water, and operates far more quietly”.

4.5.3 Induction Cook Tops

![Cook Top Ranges](a) Resistive Coil Burner; (b) Induction Cook Top.

The cooking of food by humans dates back many millennia. However, the use of electricity to cook food was experimented with only as recently as in the 1850s but did not become commercially viable until electrification of homes in the 1900s. Until the 1980s, the cook tops were based up on resistive heating coils as shown in Fig. 33(a). More recently, these types of kitchen ranges have been replaced with inductive heating elements as shown in Fig. 33(b). The inductive cook top creates a flat smooth surface that is easier to clean making it attractive to consumers. An induction cooker transfers electrical energy by induction from a coil of wire into any pot made of material which is electrically conductive and ferromagnetic. A coil of wire is mounted under the cooking surface, as shown in Fig. 34, and a large alternating current is passed through it to transfer power to the pot. When an electrically conductive pot is brought close to the cooking surface, the magnetic field induces an electrical current in the pot. The current flowing through the electrical resistance in the pot causes electrical power to be dissipated as heat. The heating of the pot can be used for cooking the food. Induction cook tops have become very popular displacing most resistive heated cook tops.
The power circuit used to deliver power to the pot via the coil must operate at a relatively high frequency of 25-50 kHz when compared with motor drive inverters. In order to reduce the switching losses in the IGBTs, the typical circuit topology is based up on resonant converters as shown in Fig. 35 and 36. Soft-switching circuit operation greatly reduces power losses during the switching transient in IGBTs providing high efficiency circuit operation. Many companies have developed optimized IGBT structures for this application due to the large market size.

Fig. 34: Induction Heating Coil and its Power Circuit Components.

Fig. 35: Half-Bridge Series Resonant Converter for Induction Heating.
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4.5.4 Induction Rice Cookers

Fig. 36: Soft-Switching Resonant Converters for Induction Heating.

Fig. 37: Rice Eating World Population.
Rice is a staple food for billions of people around the world especially in Asian countries such as China, India, and Japan, with large populations as shown in Fig. 37\textsuperscript{86}. The Asian Rice Foundation states\textsuperscript{87}: “Rice is arguably the world’s most important food. It is the second most widely cultivated cereal in the world, after wheat, and is a staple food of over half the world’s population. In much of Asia, rice is so central to the culture that the word is almost synonymous with food. In Chinese the line in the Lord’s Prayer is translated as "Give us this day our daily rice," and a Japanese proverb states that "A meal without rice is no meal." With over half the population of the world eating rice two or three times a day, it is not surprising that there are many arguments over how it should be cooked. Indeed rice can be cooked in a variety of ways, including boiling, baking, roasting, frying, and pressure-cooking. Cooking rice in an automatic rice cooker is becoming very popular, as it ensures consistent results and cooking instruction is much simpler to follow”.

![Fig. 38: (a) Induction Cooking Plate; (b) Induction Rice Cooker.](image)

Many Asian companies have developed rice cookers based on the induction heating principle. The induction heating can be accomplished by using an induction cooking plate as shown in Fig. 38(a) or preferably by using an induction rice cooker shown in Fig. 38(b). Companies that make rice cookers include Sanyo (e.g. Model ECJG10W) and Zojirushi (e.g. Model NP-HBC10/18). Two types of circuit topologies have been explored for the induction rice cooker: (a) the half-bridge series resonant converter and (b) the quasi-resonant converter. The series resonant converter has the advantages of stable switching, low cost, and streamline design. The quasi-resonant converter has the advantage of a smaller design with reduced heat sink. The quasi-resonant converter is more widely used. Due to the large market for these appliances, some semiconductor companies have developed IGBT products optimized for this market for the quasi-resonant converter topology\textsuperscript{88}. 

4.5.5 Food Processors

In the western countries, it is now commonplace to have a food processor on the kitchen counter for the preparation of food. In contrast to blenders, food processors use interchangeable blades and disks instead of a fixed blade and their bowls are designed wider and shorter for the solid or semi-solid foods usually worked in a food processor. The use of a food processor reduces the large amount of time spent in the kitchen with chopping, shredding and mixing of ingredients. A typical example is shown in Fig. 39. Manufacturers of food processors include Cuisineart, KitchenAid, and Hamilton Beach.

![Fig. 39: Typical Food Processor.](image)

**Application block diagram:** the micro-controller generates a PWM signal and controls the IGBT through the buffer-amplifier.

Fig. 40: Power Circuit for the Food Processor.
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The power circuit used for operation of the food processor is shown in Fig. 40. The AC input power is first rectified by a diode bridge to create a DC bus with a capacitor. The permanent magnet DC motor used in the food processor is then driven by an IGBT controlled chopper. The high input impedance of the IGBT allows its control with a microprocessor that can be programmed to perform various functions. This creates a compact, low-cost design suitable for the consumer market. Home appliances were an early adopter of the IGBT technology because it enhanced the simplicity and flexibility of design while deriving more functionality.

4.5.6 Vacuum Cleaners

A vacuum cleaner is an appliance that uses an air pump to create a partial vacuum to suck up dust and dirt from floors, and other surfaces. The dirt is collected by a dust-bag for future disposal. Hubert Cecil Booth invented the motorized vacuum cleaner in 1901. Since then, their use has proliferated and vacuum cleaners are now very commonly used in homes on a regular basis to maintain a healthy living environment. A typical commercial vacuum cleaner for

![Fig. 41: Typical Vacuum Cleaner.](image1)

![Fig. 42: Power Circuits for the Vacuum Cleaner using SR Motors.](image2)
household use is shown in Fig. 41. Manufacturers of vacuum cleaners include Eureca, Hoover, Bissell, and Dyson.

In the past, universal motors were mostly used for vacuum cleaners due to high operating speed with low cost. However, these motors use a mechanical brush which wears out at high speeds limiting the performance. Modern vacuum cleaners with higher output power (suction) are designed using switched reluctance motors. The power circuits used for operation of the switched reluctance motor in vacuum cleaners is shown in Fig. 42. These circuits utilize IGBTs to overcome the difficult start-up problem for switched reluctance motors and for maintaining a high operating speed. The author’s state: “Its lifetime is extended 4 times than that of conventional motor and its suction power is increased 20% at the same volume of conventional universal motor”.

4.5.7 Microwave Ovens

Fig. 43: Typical GE Microwave Ovens: (a) Table-Top Model; (b) Over-the-Range Model.

The convenience of rapidly and uniformly heating food using microwave ovens has made them an almost indispensable appliance in homes and offices. The microwave oven is now used even for stewing, frying, baking, steaming, and fermenting. Microwave ovens are designed for tabletop use or for mounting above the range as shown in Fig. 43. A microwave oven heats food by the principle of dielectric heating using microwave radiation, usually at a frequency of 2.45 GHz, through the food. Water, fat, and other substances in the food absorb energy from the microwaves resulting in heating. The microwaves interact with the food in a uniform fashion leading to food being more evenly heated throughout. The first microwave for home use was introduced by Tappan in 1955. The microwaves within the cooking cavity in a microwave oven are generated using a magnetron, which was first developed for radar applications. The cavity magnetron is a high-powered vacuum tube that generates microwaves using the interaction of a stream of electrons with a magnetic field. A typical magnetron requires about 3.5 kV between its anode and cathode terminals before current begins to flow and microwave energy is generated.
Before the availability of the IGBT, the conventional power supply for the magnetron was a ferro-resonant circuit shown in Fig. 44. Although simple in construction, this power supply was heavy and bulky due to the large size and weight of the low-frequency (50-60 Hz) step-up transformer. With the availability of the IGBT, a magnetron power supply based on using a high frequency inverter was developed as early as 1991. The block diagram for a
magnetron power supply is illustrated in Fig. 45. In this circuit, the anode voltage of the Magnetron rises above 3500 volts when the IGBT is turned on allowing it to generate microwave energy. The power delivered by the magnetron can therefore be precisely controlled using the on-time for the IGBT. Using the IGBT-based inverter circuit, the weight of the transformer could be reduced by more than 10-times from 4000 grams in the ferro-resonant converter to 380 grams. In addition, a new turbo-up mode of operation could be introduced using the IGBT-inverter to shorten the cooking time by 30 percent.

4.5.8 Flash for Cameras

Most consumers have already migrated from taking photographs using film to a digital medium. The Digital Still Camera (DSC) has now become common-place. All digital cameras incorporate a flash, as shown in Fig. 46(a), with many features such as red eye prevention. These capabilities require a digitally programmable control with very compact circuitry to drive the Xenon flash. Some cell-phones now incorporate a flash, as shown in Fig. 46(b), to improve up on the quality of photographs taken under low light conditions. In addition, electronic control of lighting is used by professional photographers with strobe flashes, as shown in Fig. 46(c). Lighting Rumours states on their website\textsuperscript{94}: "Paul C. Buff’s Einstein 640 monolights have been a big hit in the photographic lighting market, much lauded for their insulated-gate bipolar transistor (IGBT) circuitry and digital remote control."

![Fig. 46: Modern Electronic Flash: (a) Digital Still Camera; (b) Cell-Phone Flash; (c) Photographic Lighting.](image)

A typical circuit diagram\textsuperscript{95,96} for controlling the Xenon flash-bulb in a digital still camera using an IGBT is shown in Fig. 47. A Xenon bulb is used to create a short powerful burst of light with illumination characteristics close to that of sunlight. The Xenon bulb requires a high operating voltage of 320-V derived from a low 3 to 6 volt battery source. This is achieved by using a DC/DC converter with step-up transformer as shown in the figure. The high voltage is stored in a capacitor and discharged into the Xenon bulb by turning on the IGBT. The IGBTs
must have not only a high sustaining voltage capability but must be capable of operating with a drive voltage of only 4 volts. The footprint of the IGBT must also be reduced with innovative chip design and packaging because it must be capable of handling 150-A for a short duration. A similar circuit is used for the flash in a cell-phone but there is even greater pressure for IGBT manufacturers to reduce the foot-print and gate drive voltage. Some companies have described their technology roadmap for shrinking the footprint for the IGBT devices used for the flash application.

### 4.5.9 Drive Circuits for Plasma TVs

Fig. 47: Typical Circuit Diagram for Camera Strobe Flash.

Fig. 48: Plasma TVs: (a) Pedestal Model; (b) Wall-Hanging Model
Plasma TVs are an important segment of modern televisions that have displaced the previous vacuum tube models. Plasma displays derive their name because of utilizing small cells containing electrically charged ionized gases. Some of the attractive features of plasma TVs are high brightness, wide color range, and excellent viewing angle. They can be produced with very large sizes (up to 150 inches diagonally). The "dark-room" black level for plasma TVs is superior to that for LCDs. The typical power consumption for a plasma TV is 400 watts for a 50-inch screen. In order to reduce the power consumption, it is necessary to utilize energy recovery circuits. Panasonic states that PDPs will consume only half the power of their previous series of plasma sets to achieve the same overall brightness for a given display size.

A plasma display panel consists of an array of hundreds of thousands of small cells positioned between two plates of glass. A cross-section of the plasma display panel is illustrated in Fig. 49. Each cell is filled with rarefied neon, xenon, and other inert gases. The panel is comprised of sustaining (X) and scanning (Y) electrodes located on a front glass substrate, and addressing (A) electrodes located on the rear glass substrate. The X and Y electrodes are covered with dielectric and magnesium oxide layers while the Y electrodes are covered with the phosphors of the three primary colors - namely, red, green, and blue (R,G,B). A high AC pulse voltage must be applied between the X and Y electrodes to ionize the gas to create the desired plasma in the space between the front and rear glass substrates. The ultraviolet light generated in the plasma excites the three phosphors to create a color image. A full-bridge circuit configuration is usually used to convert the DC supply voltage to an AC high-voltage and high-frequency square wave pulses by the sustaining circuit. The electrodes with the intervening dielectric and
MgO layers form a capacitor that must be charged and discharged rapidly during each cycle. The energy used for the charging and discharging the capacitance was dissipated in the parasitic resistance of circuits in older generation plasma panels. This energy is now recovered using the energy recovery circuit in modern plasma panels to reduce the energy consumption.

IGBTs have enabled the development of plasma display panels with lower energy consumption. The typical sustaining circuit contains 4 IGBTs as shown in Fig. 50 while the typical power recovery circuit requires 4 additional IGBTs\textsuperscript{95}. It has been demonstrated that the power losses can be reduced by 20 percent by using IGBTs in place of power MOSFETs\textsuperscript{100}. Plasma TVs are therefore a great market for IGBTs. Many semiconductor companies have developed IGBT products tailored for this application\textsuperscript{95,98}.

### 4.6 Factory Automation and Robotics Sector

Almost immediately after I created the first IGBTs at GE, it was recognized that they could be used to make a superior factory automation product with many enhanced features due to the simplicity of control. However, it was necessary to create a complementary pair of transistors to enable control of power during both half cycles of the AC power cycle. My analysis of the IGBT indicated that, unlike power MOSFETs, p-channel devices would have nearly equivalent on-state characteristics to n-channel devices making the IGBT an excellent candidate for creating a complementary pair. The first p-channel IGBTs were successfully built directly in the GE semiconductor manufacturing facility using my design in 1984\textsuperscript{101}. This work provided the first experimental demonstration of excellent complementary IGBTs. The inferior ruggedness of the p-channel IGBT was solved using an innovative cell design called the atomic-lattice-layout\textsuperscript{102,103}. This led to the rapid deployment of a numerical controls product, called the Genius I/O, for factory automation by GE in 1986 as shown in Fig. 51(a). This product is still available from GE as shown in Fig. 51(b). The GE website\textsuperscript{104} states: “By providing distributed control on the
factory floor, Genius I/O systems offer fewer terminations to document, dramatically shorter wiring runs, and simpler, more effective troubleshooting. Genius I/O blocks automatically provide diagnostic information on field wiring, power conditions and loads, as well as the state of the communication network, blocks and circuits. Genius diagnostics sharply reduce the time needed for initial control and debugging.” The enhanced capability of the Genius I/O product catapulted GE to the number 2 position in this market. It is designed to control processes such as flow, temperature, and pressure.

Robots are in widespread use in assembly lines for building products ranging from automobiles to washing machines. Industrial automation is now heavily reliant on robots. Typical applications for factory robots are welding, painting, drilling, assembly, packaging, palletizing, and material handling. They improve the quality and speed of production while reducing cost in warehouses, shops and facilities world-wide. Industrial robots were first installed in 1961 to
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perform a die-casting application in an automotive plant. Modern factory robots are fully integrated into the factory operations. Robots performing the tasks of palletizing and assembly are shown in Fig. 52.

![Diagram of PWM amplifier circuit.](image)

**Fig. 53: IGBT-based Switching Amplifier for the T³-776 Robot.**

IGBTs have found extensive applications for the control of robots. The reasons can be understood by using the example of the T³-776 robot manufactured by Kollmorgen Inc. Prior to 1993, this robot was controlled by using Silicon Controlled Rectifier (SCR) servo loop controllers which have been replaced by IGBT-based switching amplifiers. The author’s state: “The robots performance was substantially degraded due to limitations in the CMI amplifiers. The SCR switching amplifiers created 180 Hz harmonics on their motor outputs ... resulting in unwanted harmonics superimposed on the desired motion. ... did not allow for single axis control.” The SCR switching amplifier was replaced with an H-bridge PWM switching amplifier using IGBTs as shown in Fig. 53. This solved all of the problems encountered with the SCR based controller.

### 4.7 Industrial Sector

IGBTs have found widespread applications in the industry. Squirrel-cage induction motors are dominant for AC industrial drives around the world due to their ruggedness and low-cost. As discussed in section 4.2, adjustable speed drives are now commonly used in order to achieve a high efficiency. Three-phase voltage-source inverters are the overwhelming favorite topology for industrial drive application rated for less than 2 Megawatts. Jahns and Blasko state: “During the past decade, IGBTs packaged in compact plastic power modules have rapidly expanded their voltage and current ratings so that they now dominate nearly all of the new industrial drive inverter designs...In fact, many new IGBT inverters are designed without any snubbers at all. This approach has the advantage of saving cost, space, and losses in the inverter – all positive effects.”

A typical large industrial motor is shown in Fig. 54. Such motors are commonly used in industries such as (a) manufacturing; (b) water and waste management; (c) food processing; (d) petroleum; (e) lumber; (g) plastics; (h) chemicals; (i) printing press; and (j) steel. For industrial
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systems with power ratings of up to 25 MW, ‘IGBTs have become completely dominant for low-voltage converters and are increasingly used for medium–voltage converters’ according to Siemens.\textsuperscript{107}

4.7.1 Textile and Rolling Mills

The use of IGBTs is motivated by the energy savings potential offered by variable-speed drives in rolling mills shown in Fig. 55(a) and textile mills shown in Fig. 55(b). The use of IGBT-based variable-speed drives in textile mills has been found to reduce noise while providing the benefits of reduced drive size, reduced cost of operation, and increased drive performance.\textsuperscript{108} The transition from DC motors to AC motors by the metal-processing industry has been documented. Applications, such as finishing mills, roughing mills, roller-tables, loopers, shears, etc, can now all be served using AC motors. Bhoopapur\textsuperscript{109} states: “The early generation of ac drives were
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lacking in dynamic and static accuracy, power ratings were low, expensive when compared with DC motor drives. These problems were overcome with the availability of vector-control and IGBT based ac drives.” Both Hot-Mills and Cold-Mills now utilize PWM IGBT inverters for operation of AC motors.

4.7.2 Arc and Tube Welding

Arc and tube welding machines are commonly used in industrial setting for building and repair of the infrastructure. Welding power supplies, such as those shown in Fig. 56, are required to create an electric arc between an electrode and the base material to melt the metals at the welding point. The arc can be created by either DC or AC current with consumable or non-consumable electrodes. The welding region is sometimes protected by some type of inert or semi-inert gas. Arc welding is popular due to low capital and running costs. For arc welding, the voltage is

![Welding Power Supplies](image1)

![Welding Power Supplies](image2)

**Fig. 56:** Welding Power Supplies: (a) Arc; (b) Tube

![IGBT-Based Welding Power Supply Circuit](image3)

**Fig. 57:** IGBT-Based Welding Power Supply Circuit

Arc and tube welding machines are commonly used in industrial setting for building and repair of the infrastructure. Welding power supplies, such as those shown in Fig. 56, are required to create an electric arc between an electrode and the base material to melt the metals at the welding point. The arc can be created by either DC or AC current with consumable or non-consumable electrodes. The welding region is sometimes protected by some type of inert or semi-inert gas. Arc welding is popular due to low capital and running costs. For arc welding, the voltage is
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directly related to the length of the arc, and the current is related to the amount of heat input with typical currents of 50 to 500 amps depending on the size of weld. For arc welding with low voltages and large currents, a soft switching PWM DC-DC power converter with IGBT switches in the primary side of a high frequency transformer, shown in Fig. 57, is considered to be the most suitable topology for the welding power supply\textsuperscript{110,111}. The welding power supply and internal components are shown in Fig. 58. Power losses in the IGBTs are reduced by using soft-switching resulting in a volume reduction of 59% and weight reduction of 47% compared with the hard-switching approach. Dynamic welding performance is improved due to operation at 40-kHz when compared with 13-kHz with hard-switching.

Tube welding and quenching applications require an induction heating approach with high power and operating frequency\textsuperscript{112}. A multiple frequency converter circuit is shown in Fig. 59 which uses IGBTs with zero-current-switching (ZCS) to reduce switching losses. This allows

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\textbf{Fig. 58:} (a) CO2/MAG arc Welding Power Supply for 220V-rms and 400V-rms input; (b) Assembled Components in Soft Switching PWM DC-DC Power Converter.

\textbf{Fig. 59:} Multiple Frequency IGBT-based Induction Heating Power Supply for Tube Welding.
increasing the operating frequency up to 250-kHz which is suitable for tube welding and quenching.

### 4.7.3 High Speed Drilling and Milling

![Fig. 60: (a) Milling Machine; (b) Drilling Machine](image)

Manufacturing facilities are equipped with milling and drilling machines, such those shown in Fig. 60. In order to increase the throughput, it is necessary to employ high-speed cutting technology by improving the efficiency of the cutting process. Milling spindles with extremely high rotational speed and great stiffness are required for high performance milling operations. Active magnetic bearing must be used to meet these requirements for high speed milling spindles. The basic control circuit for an active magnetic bearing is illustrated in Fig. 61. The amplifier must provide sufficiently high voltage to obtain the desired slew rate. The amplifier voltage must be much larger than the voltage drop across the resistance of the magnet coil in order to obtain large stiffness. The author’s state: “In order to improve the reliability and reduce the cost of the whole system, IGBT devices are used in the newly developed switching amplifier. The newly developed IGBT power amplifiers have been tested in a practical system of a high-speed milling spindle (35 kW/40,000 rpm) consisting of active magnetic bearings for five axes.”

![Fig. 61: (a) Active Magnetic Bearing; (b) IGBT Circuit](image)
High speed drilling can also be accomplished by electrical discharge machining which uses a controlled electric spark to erode the metal in a work-piece. The basic diagram of this system is illustrated in Fig. 62(a)\textsuperscript{114}. Electrical discharge machining removes material from high hardness conductive work-pieces by using a series of repeated electrical discharges between an electrode and the work-piece. Dielectric fluid is forced into the gap where the electrical discharge is occurring. The dielectric fluid breaks-down when a sufficient voltage is applied to the electrode creating a spark. The electric and magnetic fields produce a tensile force that tears-off particles from the molten and softened metal leading to the desired hole. The circuit diagram for electrical discharge milling, shown in Fig. 62(b), utilizes IGBTs to generate high voltages across the gap between the electrode and work-piece with a trapezoidal saw-tooth pulse waveform.

4.7.4 Industrial Boilers and Dryers

Fig. 62: (a) Electrical Discharge Machining; (b) IGBT Circuit

Fig. 63: (a) Nordson Induction Dryer; (b) Pirobloc Induction Oil Heater
The processing of materials in the industry often requires heating of fluids (liquids and gasses) with high uniformity and throughput. The electromagnetic induction based heating of fluids is applicable to boilers, dryers, hot-air producers, oil-heaters, etc., in industrial and chemical plants. An induction heating based compound dryer for industrial applications made by Nordson is shown in Fig. 63(a). It occupies only a fraction of the floor space of conventional dryers and is specifically designed for production lines with speeds of 500 to 2200 ends per minute. An induction heating based oil heater made by Pirobloc is shown in Fig. 63(b).

A typical induction heating system based upon using IGBTs for the heating of fluids is shown in Fig. 64. The thin metal chamber housing the fluid is heated by eddy currents generated from inductive coupling of power from outer working coil. A series resonant PWM inverter using IGBTs is used for producing the high frequency power fed to the working coil.

4.7.5 Industrial Machine Tools

With demands for faster machining processes, higher holding forces are required for tools in the machining industry. Since mechanical tool holders are reaching their limits of performance, new thermally induced diameter change based tool holders are being introduced. In this approach, the tool holder is a solid ring that is rapidly expanded by inductive heating to release the tool and then rapidly cooled to shrink it to hold the replacement tool. The tool holder is located inside an inductive heating coil as shown in Fig. 65(a). A schematic diagram of the IGBT-based inductive heating power supply is shown in Fig. 65(b). The system is capable of providing up to
10-kW of power to the tool-holder at 100-kHz. ECONOPACK FP35R12KS IGBT modules from EUPEC are used because they can operate at 100-kHz output frequency.

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4.8 Publishing Sector

The printing of newspapers requires high speed winders with precision positioning. A typical newspaper printing press is shown in Fig. 66(a). A typical paper machine winder load is cyclic in nature with the following steps: (a) acceleration for 1 minute, (b) winding for 8 minutes, (c) deceleration for 1 minute, and (d) set change for 2 minutes. Regenerative braking is used to obtain a high operating efficiency in order to reduce operating cost. The circuit diagram for driving the AC motors is shown in Fig. 66(b). The author states: “The synchronous rectifier
The Insulated Gate Bipolar Transistor provides smooth motoring and regenerative capability with six IGBTs in a single three-phase, full-wave bridge configuration. Its regulator can control power factor close to unity or it can be set leading to supply vars to the AC power system.” This system has been installed on two paper machine winders at Rainy River Forest Products in Ontario, Canada.

4.9 Medical Sector

Advanced medical diagnostic equipment has revolutionized the quality of care for our society. Non-invasive imaging of the interior of the body enables the surgeon to perform operations while minimizing damage to adjacent tissue and organs. The IGBT has been used since the early deployment of CT and MRI scanners for the control of the gantry on which the patient is reclining as described below. It is also used in the power supply for X-ray and Ultrasound machines. In addition, hundreds of thousands of lives are being saved due to the availability of portable defibrillators which require IGBTs for delivering the controlled shock to the patient of cardiac arrest as discussed below.

4.9.1 CT and MRI Scanners

Computed tomography (CT) generates a three dimensional image of a patient using a large series of two dimensional images taken around a single axis of rotation. The image is generated by viewing the patient using x-ray imaging from numerous angles. A single plane of a patient is scanned from various angles in order to provide a cross-sectional image of the internal structure of that plane. A three-dimensional view can then be created by mathematical analysis that combines the images. The gantry on which the patient is reclining is positioned using closed-loop feedback control of motors in order to accurately move and position the patient. An IGBT-
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based motor drive is employed by all manufacturers, such as GE, Philips, and Siemens, for precise and controlled movement of the gantry. The GE Prospeed CT scanner is shown in Fig. 67(a). The CT scanner contains an X-ray tube with detectors located diametrically opposite the X-ray source, as shown in Fig. 67(b), which are rotated around the patient to generate a section image. CT scanners can provide detailed cross-sectional images of nearly every part of the human body including the brain, neck, shoulders, cervical spine, heart, lungs, abdomen, liver, kidney, pelvis, etc.

Fig. 68: (a) GE Discovery MRI Scanner; (b) Imaging Technology

Fig. 69: Closed-Loop IGBT-based Gantry Positioning System.
Magnetic resonance imaging (MRI) is another important diagnostic tool commonly used in hospitals to determine the nature of injuries and status of organs in patients. Unlike CT scans, no radiation occurs when using an MRI procedure. In an MRI machine, a powerful magnetic field is used to align the magnetization of some atoms in the body, and radio frequency fields are used to systematically alter the alignment of this magnetization. The nuclei in selected atoms produce a rotating magnetic field detectable by the scanner which is used to construct an image of the scanned area of the body. MRI is especially useful in imaging the brain, muscles, heart, and cancers compared with other medical imaging techniques such as computed tomography (CT) or X-rays. It can detect aneurysms, damage to the heart or blood vessels, torn ligaments, and to find tumors.

The basic closed-loop system used to accurately position the gantry in MRI and CT scanners is illustrated in Fig. 69\textsuperscript{119}. IGBT inverters for the gantry are available for various CT models such as the Siemens SOMATOM AR.STAR, the Philips Tomoscan SR 7000, the Shimadzu SCT-5000T, and GE Healthcare Mobile HiSpeed LX/i. In addition, the high voltage needed for the X-ray tube in the CT scanner is generated using IGBTs.

### 4.9.2 X-Ray Machines

![Fig. 70](image)

Fig. 70: (a) Wilhelm Roentgen; (b) William Coolidge

X-rays were discovered by Wilhelm Roentgen, shown in Fig. 70(a), in 1895. X-rays are electromagnetic radiation with a wavelength of 0.1 to 100 angstroms. Hard X-rays with wavelengths of 0.1 to 1 angstroms have penetration abilities that make them suitable for generating images of the interior of human bodies. Today, X-rays are usually generated by using the X-ray tube developed by William Coolidge, shown in Fig. 70(b), for the continuous production of X-rays. [I have the privilege of receiving the Coolidge Award at GE in 1983 for my work on the invention, development, and commercialization of the IGBT.] In the Coolidge tube, a high voltage is used to accelerate electrons emitted from a filament to gain high energy. The electron beam is directed to a target, usually tungsten, to excite the X-rays. The energy of the X-rays corresponds to the maximum energy of the electrons which is accelerated typically by
70 kV. The X-ray production processes are very inefficient (< 1%) leading to the need for high electron beam energy. Typical X-ray machines used for medical diagnostics are shown in Fig. 71. The X-ray machine power supply must operate at very high voltages (20-150 kV) while delivering sufficient current to produce the X-ray beam required to create images. The range of voltages and current required to fulfill various requirements for Fluoroscopy and Radiology are shown in Fig. 72.

![X-Ray Machines](image1.png)

(a) Stationary; (b) Mobile; (c) Dental

![Graph](image2.png)

Fig. 72: Wide Range of X-Ray Power Supply Voltages and Currents.
An X-ray image allows examination of dense material within human tissue. The most common application is examination of bone fractures. In addition, it is routinely used to discover cavities in teeth at dentist facilities. With the advent of terrorism attacks focused on airlines, all passengers must now endure going through a security point where their baggage is screen through a X-ray scanner as shown in Fig. 73. The X-ray scanner allows imaging the contents of a bag without the time consuming task of rifling through the contents and can observe weapons hidden in concealed compartments.

Fig. 73: Airport X-ray Scanner for Baggage

A block diagram for the typical X-ray machine power supply is shown in Fig. 74. The input AC voltage is rectified and fed to a high-frequency PWM resonant inverter that is based up on IGBTs. This allows using a high-frequency transformer to create the very high voltages
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needed for the X-ray tube operation while keeping the size and weight small. The output of the high-frequency transformer is rectified to generate the desired DC voltage for the X-ray tube. The dynamic response of the X-ray power supply must be fast and its DC output voltage must reach steady-state in a short time to prevent noise and defects in the X-ray image. These requirements can be met by using an IGBT based PWM resonant inverter whose circuit diagram is shown in Fig. 75\textsuperscript{121}.

![Circuit Diagram](image)

Fig. 75: Typical Power Supply for X-ray Machine.

4.9.3 Ultrasound Machines

![Ultrasound Machines](image)

Fig. 76: Ultrasound Imaging Machines: (a) Table-Top Model; (b) Portable Model
Ultrasound based diagnostic imaging is widely used by cardiologists, neonatologists, obstetricians, urologists, gastroenterologists, etc, for diagnosis and treatment of patients. Ultrasounds are sound waves above the audible range for humans. The choice of the ultrasound frequency for diagnostic purposes is a trade-off between image resolution and spacial depth. Lower ultrasound frequencies penetrate deeper into the body but produce images with less resolution due to the longer wavelength of the sound wave. Typical ultrasound frequencies range from 2 to 18 MHz. Sonography is performed using a hand-held probe, visible in the image in Fig. 76(a), that is placed and moved over the patient while observing the image in real time. The probe contains a piezoelectric transducer with a phased array to allow altering the direction and depth of the sound wave. The sound wave is reflected from the organs inside the body at different intensities depending up on their composition and the time taken for the echo to return to the transducer indicates the distance travelled by the wave. This information is converted to an image for diagnosis.

The sound wave from the ultrasound transducer is generated by the application of a high voltage pulse to the piezoelectric medium. The pulse must have an amplitude of over 1000 volts with a current of 20-50 amperes. A typical circuit used to drive the transducer is shown in Fig. 77\textsuperscript{122}. Due to short duration of the pulse, typically 0.5 microseconds, with a low operating frequency of 200-Hz, the best approach is to slowly charge a capacitor (C3) through a diode (D2) when the IGBT is off and then turn-on the IGBT for the short pulse duration to discharge the capacitor through the transducer.

4.9.4 Portable Defibrillators

One-fourth of all deaths in the developed world occur due to cardiac arrest\textsuperscript{123}. Eighty-five percent of deaths from sudden cardiac arrest occur due to ventricular fibrillation. Without synchronization of heart muscles, blood flow through the body is interrupted leading to starving oxygen from organs. The victim will almost certainly die within 10 minutes unless aid is provided. A defibrillator applies a dose of electrical energy to the heart muscles which
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depolarizes a critical mass of the heart muscle, terminates the arrhythmia, and allows normal heart rhythm to be reestablished. It is essential that the defibrillator be located close to the victim and be easily operated to provide the life-saving response within 10 minutes. Automated external defibrillators (AED) are now widely deployed in places such as corporate and government offices, shopping centers, airplanes, airports, restaurants, hotels, sports stadiums, schools and universities with a high density of aging populations. Typical portable automated external defibrillators are shown in Fig. 78(a) and (b). The automated external defibrillator is designed to provide simple voice commands to prompt the administration of the live-saving electrical jolt to the victim. According to USA Today, about 450,000 people die each year in the U.S. from sudden cardiac arrest. Among these victims, the American Medical Association (AMA) estimates that more than 100,000 lives can be saved by the availability of modern AEDs enabled by IGBTs.

Modern AEDs utilize a biphasic shock voltage. The first shock phase charges the heart cell membranes while the second shock phase returns them to zero voltage. Typically, a 100-kW shock must be delivered to the heart using a 2000-V source. The basic H-bridge circuit, shown in Fig. 79, with four IGBTs is used in an automatic external defibrillator. In this circuit, a
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capacitor charged to 2000-V is first discharged for 5-8 milliseconds by turning on two of the IGBTs to deliver the main shock in the first phase. The other two IGBTs are then turned-on to deliver the shock for the second phase by using the residual charge in the capacitor in the opposite direction. A compact portable AED could not be built until the use of IGBTs to replace arc relays.

Implantable defibrillators, such as the one shown in Fig. 78(c), are surgically inserted into the body of patients at high risk of sudden cardiac death. Young adults have been diagnosed with ‘long QT syndrome’ that can lead to unconsciousness and death during intense physical activity due to ventricular arrhythmias. The implantable defibrillators is designed to detect arrhythmia of the heart and provide a jolt of electricity to avoid fibrillation. In their book, Prutchi and Norris state\(^{124}\): “Implantable defibrillators commonly use insulated gate bipolar transistors (IGBTs) to switch defibrillation energy to the heart.” Some companies have developed IGBT specifically tailored for the implantable defibrillator market\(^{125}\).

4.10 Aerospace Sector

Early flying machines used hydraulics for control of flight surfaces. Until the 1990s, hydraulic power was used in almost all commercial aircraft for actuator functions such as the landing gear, nose-wheel steering, braking, and adjustment of flight surfaces. Aircraft hydraulic systems are costly, labor-intensive to maintain, suffer leakage problems, and pose contamination hazards. By the early 1990s, progress with motors driven by power electronics using IGBTs had produced an attractive alternate technology with a very high power-to-weight ratio of more than 10 kW/kg\(^{126}\). This ‘dry’ all-electric alternative offered improved aircraft safety and reduced design, development, and testing costs. Cronin states: “In a Lockheed study of a 500-seat international
commercial transport aircraft, the net value of all-electric/electronic technologies was $5 Billion based on a fleet of 300 planes with operating life of 16 years.”

The ‘More Electric Aircraft Initiative (MEI)’ proposed by Wright Patterson Airforce base with Sundstrand Corporation embraces utilizing electrical power for driving aircraft subsystems such as flight control actuation, environmental control, lubrication, and fuel pumps. They have developed an electromechanical actuator to increase the power density of the motor drive to 1 kW/lb with an efficiency of more than 80 percent. The power electronics module is comprised of IGBTs as inverter switches in a soft-switching topology.

The Boeing 787 Dream-Liner passenger airplane shown in Fig. 80(a) was recently introduced with much fan-fare. It is designed to seat 234 passengers in a three-class setup, or 240 in two-class domestic configuration, or 296 passengers in a high-density economy arrangement. It can fly 8,000 to 8,500 nautical miles which is sufficient to cover the Los Angeles to Bangkok or New York City to Taipei routes. Its new electrical architecture replaces bleed air and hydraulic power sources with electrically powered compressors and pumps, and completely eliminates pneumatics and hydraulics from engine starters or brake subsystems. The two major innovations made in the 787 design are (a) use of composite materials to reduce weight by 20 percent, and (b) the replacement of hydraulic systems with electrical actuators. The article states: “Virtually everything that has traditionally been powered by bleed-air from the engines has been transitioned to an electrical architecture. The affected systems include: engine start, auxiliary power unit (APU) start, wing ice protection, cabin pressurization, and hydraulic pumps.”

The Airbus A380 commercial passenger airplane is shown in Fig. 80(b). This aircraft is also heavily reliant up on IGBT based power electronics for replacement of hydraulic systems. A fault tolerant IGBT-based inverter has been created for the Airbus by Siemens. Typical power electronic modules are those supplied by Hispano-Suiza, a Safran Group Company: the ETRAS electrical thrust reverse actuation system.

![IGBTs](image)

**DC-DC CONVERTER SCHEMATIC**

*Fig. 81: Typical Power Electronics used in More Electric Aircraft*
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The ‘All-Electric’ or ‘More-Electric’ aircraft require DC-DC converters and DC-AC inverters for use in various systems described above. A typical DC-DC converter using IGBTs is shown in Fig. 81\(^{131}\). A resonant circuit topology is used to allow the circuit to operate at 120-kHz which reduces the size and weight of the transformer - a critical factor in aircraft electronics design. The reliability and thermal stability of IGBTs in plastic modules has also been documented\(^{132}\). These modules are typically mounted on the aircraft engine as illustrated in Fig. 82.

![Image of IGBTs and aircraft engine](image)

Fig. 82: Power Electronics mounted on Aircraft Engine.

4.13 Marine Propulsion Applications

![Image of cruise ship and cargo ship](image)

Fig. 83: (a) Cruise Ship; (b) Cargo Ship.

With the availability of high power induction motor drives based up on IGBTs, more and more ship designers are moving to electrical propulsion systems\(^{133}\). The authors state: “In the recent years, there is a huge demand by ship owners and ship yard operators for electric propulsion
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based solutions in order to ease their maintenance efforts and to enhance their efficiency and durability levels.” The propulsion design has to be compact, robust, and easy to install and operate. Medium voltage Press-Pack IGBT converters are available for this application with a wide range of power handling capability up to 33 Mega-Watts. On the commercial side, the marine propulsion applications include cruise liners [such the one shown in Fig. 83(a)], LNG carriers, crude oil tankers, and container ships [such as the one shown in Fig. 83(b) for transporting cars].

![Typical Cruise Liner MV7612 architecture.](image)

A typical cruise ship propulsion system requires a redundant architecture\textsuperscript{133} as illustrated in Fig. 84. For large Cruise Liners, a slow speed, direct drive induction motor is fed by two completely independent 6.5 kV electrical drives. Two 12-pulse transformers feed the two 12 Mega-Watt, 6.6 kV, MV7612 converters containing IGBTs. The fully redundant arrangement allows operation using a single converter with at least 50% torque in case of failure of the other converter.

![Typical LNG Carrier.](image)
A LNG carrier is used for transport of liquefied natural gas. The fleet of LNG carriers is growing rapidly due to the demand for natural gas around the world. A typical LNG carrier is shown in Fig. 85. Most LNG carriers are designed with a single skeg hull shape using electrical propulsion with a single stage gearbox fed by two medium speed motors to obtain redundancy. The circuit configuration for the LNG carrier drive is illustrated in Fig. 86. Two medium speed induction motors are fed by a single 3.3 kV electrical chain to create a 16 Mega-Watt, 3.3 KV system.

Older generation Ro-Ro (Roll On – Roll Out) car carrier vessels, such the one shown in Fig. 83(b), also utilize IGBTs for supplying electric power within the ship. The typical power requirements are 1.44 Mega-watts using a 440-V, 60-Hz AC source. It is necessary to use a IGBT based power converter to convert the variable frequency power from the shaft to a well regulated constant frequency and voltage because the main ship engine operates at a variable
speed from 64 to 155 rpm. Five Ro-Ro car carrier vessels using the IGBT based ship-board power source were already under continuous operation in the North and South Atlantic routes by 2004.

Many power semiconductor companies have developed press-pack modules to serve this high power motor drives market. Two examples are shown in Fig. 87. These modules typically contain multiple IGBT chips to provide the desired high current handling capability as shown in Fig. 87(a). Siemens specifically targets their IGBT modules for marine drives\cite{135}.

### 4.12 Defense Sector

The defense industry is most often an early adopter of new technology because it is able to absorb the initial high cost of a nascent technology while taking advantage of its performance attributes. The IGBT is no exception in terms of its adoption for military applications. It is worth pointing out that the U.S. Defense Department, which accounts for 93 percent of Federal energy use, is now pushing for the use of electric vehicles and improved efficiency\cite{136} according to John Holdren, Director of White House Office of Science and Technology Policy.

#### 4.12.1 Hybrid Electric Armored Vehicles

The M113 Troop Carrier, shown in Fig. 88, is a fully tracked armored personnel carrier that has formed the backbone of the United States Army's mechanized infantry units for the last 50 years. It can handle 11 passengers with a crew of 2. A hybrid electric version of the M113 troop carrier has been developed by the U.S. Army\cite{137} with 200 kW capability. The move to hybrid electric drive is motivated by reduced weight, greater design flexibility, faster acceleration, greater fuel economy, reduced noise and thermal signatures, and improved vehicle diagnostics. The hybrid electric drive is also planned for the Bradley fighting vehicle shown in Fig. 89. The Bradley
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fighting vehicle is used by the U.S. Military to scout enemy positions and transport troops into hostile territory. It is a 500-horsepower, amphibious vehicle with enough armaments to destroy enemy tanks and provide protective fire for the troops it carries to battle. Due to its substantially larger weight, the Bradley Fighting Vehicle requires a much more powerful hybrid electric power system with an induction-motor-based sprocket drive system and a 275-kW auxiliary power unit.

![Bradley Fighting Vehicle](image)

Fig. 89: Bradley Fighting Vehicle.

![Converter Diagram](image)

Fig. 90: Typical Non-Isolated Bi-directional Three-Phase Converter.

The link between the battery and the propulsion bus is a critical link in any hybrid electric vehicle. In combat vehicles, it is necessary to achieve a high volumetric power density approaching 6 kW per liter. In addition, it is preferable for the power electronics to operate at high temperatures to reduce the cooling requirements. This has been achieved with IGBTs at the U.S. Army Research Laboratory by using the three-phase bi-directional DC-DC converter shown in Fig. 90. The converter was constructed using 400-A, IGBT modules from Powerex (CM400DU-24NFH) and Eupec (BSM300GB120DLC) operated at a switching frequency of 20 kHz.
4.12.2 Naval Ships and Submarines

The U.S. Navy has a program operational since the 1990s to replace all hydraulic actuation systems because they are noisy, inefficient, bulky, and require continuous maintenance. The goal is to drive everything that moves on a ship, aircraft-carrier, or submarine with electromechanical actuators. The ‘Power Electronics Building Blocks (PEBB)’ program\textsuperscript{139,140} was initiated by the Office of Naval Research (ORN) to create a reliable modular scalable element to achieve a major reduction in cost, losses, size and weight of power electronics. The basic PEBB concept is shown in Fig. 91(a)\textsuperscript{141}. The PEBB is capable of performing power conversion while handling any internal power dissipation. It has the built-in intelligence to sense its environment on the input and output side to create a plug and play architecture. Today, the PEBB is implemented using IGBTs as shown in Fig. 91(b)\textsuperscript{139}.

The power distribution architecture in naval ships is illustrated in Fig. 92.\textsuperscript{142} It consists of creating a DC power distribution bus utilizing the energy generated from the prime mover/generator set. Multiple AC to DC and DC to AC converters are required to create the DC bus and then deliver the power to various loads such as auxiliary power, actuators, high power sensors, and pulse power weapons. All of these converters contain IGBTs as the power switching devices.

Electromechanical actuators (EMA) have replaced hydraulic actuators in naval vessels, such as the submarines and aircraft carriers\textsuperscript{143} shown in Fig. 93. According to the author: “EMA technology is now feasible with a potential growth of the technology of 8 orders of magnitude over the two decades from 1990-2010.” The electromechanical actuators are required for weapons handling, weapons elevators, aircraft elevators, hangar doors, rudders, etc. The EMA technology showed significant reduction factors (benefits): machinery weight reduction by 3.23x, machinery space reduction by 0.18x, energy efficiency improvement by 2.32x, maintenance improvement by 2.70x, reduction of machinery complexity by 2.23x, and reduction
of personnel by 2.92\times. In absolute terms, a total weight reduction of 1,400,000 lbs, space reduction by 60,900 sq.ft. and personnel reduction by 500 was found for a typical naval vessel, leading to a reduction of the cost of deployment of the ship by \$20 million per year.

When a primary power source in naval ships is interrupted, static automatic bus transfer switches (SABT) use power switching elements to transfer loads from the primary power source to an alternate power source\textsuperscript{144}. According to the authors: “Over 500 SABTs have been
successfully installed on US Navy destroyers, submarines, and aircraft carriers.” The study concluded that the IGBT is suitable as a transfer switch with close to ideal seamless operation. The reliability of IGBTs for the AC/DC link motor generators in ASTUTE class nuclear submarines has also been studied\textsuperscript{145}. The study included five ASTUTUE class submarines under deep thermal cycling. The study concluded: “A high degree of confidence can be taken that the in service thermal cycling duty will not cause any degradation in the performance characteristics of the IGBT power switches”.

4.12.3 Directed Energy Weapons

The U.S. Navy is moving towards replacing traditional weapons based on chemical processes with directed energy and electric weapons\textsuperscript{146}. All the electric weapons require pulsed power with stored energy in the range from 10 kilo-Joules to Giga-Joules and instantaneous power levels exceeding 20 Giga-Watts. Large electro-magnetic (EM) rail-guns, such the one shown in Fig. 94(a), have a range in excess of 200 miles for a 20 kg projectile. This requires pulsed power with over 100 Mega-Joules of energy delivered with a 5 Mega-Ampere, 20-kV, few millisecond jolt. The ship-board rail gun, illustrated in Fig. 94(a), houses the heavy pulse power system below deck as a ship-ballast to ensure good center of gravity and buoyancy.

Ship defense against subsonic and supersonic anti-ship cruise missiles requires the development of high energy lasers with a power of 1-4 Mega-Watts for a dwell time of a few seconds. This is generated using over 100 Mega-Joules of stored energy per engagement. For self-defense, the laser and pulse-power system must be housed together, as shown in Fig. 94(b), on top of the ship-deck making size and weight of the pulse power system critical.

![Ship layout for a long range railgun powered by three pairs of pulsed alternators. (Courtesy NSWC)](a)

![Ship self-defense concept.](b)

Fig. 94: Directed Energy Weapons: (a) Long-Range Rail-Gun; (b) Laser Self-Defense.
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The 120-kV, 23-A pulse power supply for a Pierce Electron Gun under development at the Los Alamos National Laboratory is shown in Fig. 95. It is capable of producing 10 microsecond wide pulses at a repetition rate of 10-Hz. Six Metglas cores are utilized with one EUPEC IGBT driving each core of the step-up transformer to generate the 120-kV, 23-A pulse.

![Diagram](image)

Fig. 95: Pulse Power Supply for Pierce Electron Gun.

4.13 Financial Sector

At first glance, it is not obvious that power electronics and the IGBT have an impact in the financial sector of the economy. However, the financial sector is dependent up on the availability of high nines power quality to operate the computers and servers required for uninterrupted financial transactions. Any glitch in the power source that cause blackouts, brownouts, or even voltage fluctuations can produce huge financial losses. Banks, insurance and financial services

![UPS Units](image)

Fig. 96: UPS Units: (a) Shenzen Units; (b) Mitsubishi Unit.
must protect themselves against power fluctuations by the installation of uninterruptible power supplies (UPS) that makes the load power independent of mains voltage and frequency fluctuations. IGBT based PWM inverter switching technology is widely used to create the UPS systems that are deployed in the financial sector because of their reliable performance with high efficiency. Due to the large market, a large number of companies around the world have developed UPS systems with a wide range of power handling capability. Some examples of UPS units are shown in Fig. 96.

![Fig. 97: UPS Circuit Topology.](image)

The basic circuit topology used in a typical UPS system is shown in Fig. 97. In the rectifier stage, the input AC voltage is rectified to produce a DC bus across the capacitors. The regulated output AC voltage is produced by the inverter stage. The IGBT is extensively utilized for both the rectifier and inverter stages. Many UPS suppliers tout the use of IGBTs in their UPS products due to the high performance and reliability achieved with these devices.

### 4.14 Power Transmission and Distribution Sector

Power transmission is generally performed over long distances because of the geographical separation between the energy source and the end user. The power sources are typically hydroelectric dams, nuclear power stations, or coal-fired power plants. There is also an increasing interest in the generation of electricity from renewable energy sources such as wind-power and solar-power. Typical end users are residences, offices, and factories. The power from the source can be transmitted to the end user by using either an AC or DC power transmission system. DC power transmission is favored over AC power transmission because of cable charging losses in an AC-system which limit the power transmission distance. This particularly true for submarine cables but is also applicable to landlines. The cost of AC power
transmission is also increased because more AC lines are needed to deliver the same power over the same distance due to system stability limitations, the need for intermediate switching stations, and the need for reactive power compensation. Further, back-to-back converters with asynchronous HVDC links act as an effective firewall against propagation of cascading outages.

A typical HVDC power transmission system is illustrated in Fig. 98. The power is transmitted at very high voltages (above 100-kV) in order to reduce the current on the cables. Large currents in cables require more copper which adds to the cost and weight. Since power semiconductor devices are unable to withstand such high voltages, it is necessary to connect many devices in series to satisfy the system requirements. In addition, for higher power levels, many devices may have to be connected in parallel as well. The series and parallel combination of power devices comprises an HVDC valve. The most common configuration for modern overhead HVDC transmission lines is bipolar because it provides two independent DC circuits each capable of operating at half capacity. Two basic converters topologies are used in modern HVDC transmission systems: conventional line-commutated, current-source converters (CSC) based up on thyristor-valves and self-commutated, voltage-sourced converters (VSC) based up on IGBT-valves. Each valve consists of a large number of series connected thyristors or IGBTs to sustain the desired DC voltage rating. In the case of current source converters with thyristor-valves, a Graetz bridge configuration is used allowing six commutations or switching operations.
per period. Self-commutated, voltage-source converters using IGBTs are preferred because they allow independent rapid control of both active and reactive power. Reactive power can also be controlled at each end of the transmission line providing total flexibility in network design.

The self-commutated, voltage source converters can be constructed using IGBTs without the snubbers required for GTOs, as illustrated in Fig. 99. The rate of rise of the current in the IGBT can be controlled by tailoring the gate drive voltage waveform without any auxiliary components. This allows controlling the reverse recovery of the anti-parallel rectifiers without the snubbers. The reduced passive components in the IGBT-based VSC inverters reduce system cost. The IGBT-based H-bridge configuration shown in Fig. 99 is remarkably similar to that used for motor control application as discussed in the previous sections. Consequently, voltage source converters with pulse width modulation have evolved. The high commutation frequency used in these VSCs allows elimination of the converter transformer leading to the concept being called ‘HVDC Light’\textsuperscript{152}. This approach is also attractive for connecting groups of windmills to an overall network\textsuperscript{153} and for power transmission from offshore wind farms\textsuperscript{154}.

### 4.15 Fossil-Fuel Power Generation Sector

Among the legacy power generation technologies, gas turbine power plants are being deployed due to the discovery of large amounts of natural gas in the United States and Australia. A permanent magnet generator is run directly from a gas turbine without a gear-box for enhanced reliability. The generator terminal voltage is at a nominal 600-Hz which must be rectified and then converted to a well regulated 50 or 60 Hz AC power for transmission to points of use. IGBT power switches are now being used for this application because of the availability of high-voltage, high-current modules from many manufacturers. A 1.6 Giga-Watt gas power plant can
be designed using 6 modular 300 kVA three phase voltage source IGBT stacks with 6 IGBTs in a typical bridge configuration\textsuperscript{155}. The main parts of the power plant are shown in Fig. 100. The design allows full control of the AC current and power factor on the grid-side. The IGBT stacks are paralleled to satisfy the 1.6 Giga-Watt power requirements. The availability of intelligent IGBT power modules with gate drivers and protection circuits has accelerated the adoption of this technology.

4.16 Renewable Energy Power Generation Sector

![Graph showing electricity production by source](image)

Fig. 101: U.S. Electricity Generation.

![Wind farm and solar panels](image)

Fig. 102: Renewable Energy: (a) Wind-Power; (b) Solar-Power.
The production of electricity in the United States is mainly achieved by burning fossil fuels such as coal and natural gas as shown in Fig. 101. It is noteworthy that the demand for electricity is steadily increasing since the 1980s with no sign of abatement. The increased demand for electricity is being served by the installation of electricity generation plants based on fossil fuels. Since fossil fuels produce carbon dioxide emissions, it would be preferable to enhance the deployment of electricity production using renewable energy sources such as wind-power and solar-power. At the recent (May 2011) Doha conference, the U.N. Intergovernmental Panel on Climate Change published a report\textsuperscript{156} stating: “It is likely that renewable energy will have a significantly larger role in the global energy system in the future than today.”

The renewable energy sources shown in Fig. 102 are considered the most promising options in the near future. According to the U.S. Department of Energy, offshore wind farms, such as the one shown in Fig. 102(a), alone could produce 900 Giga-Watts of power which is sufficient to supply the needs of the entire United States. According to the European Photovoltaic Industry Association, solar energy reaching the earth, converted to electricity using solar-farms, such the one shown in Fig. 102(b), could satisfy global energy needs 10,000 times over. Other renewable energy sources include wave-power, geothermal-power, etc. In the first six months of 2010, 11 percent of the electricity produced in the U.S. came from renewable energy sources. In March 2011, China released its new five-year plan with goals of 11.4 percent of energy generated using non-fossil fuels\textsuperscript{157}. The IGBT is a critical technology required for the deployment of all renewable energy sources.

### 4.16.1 Wind Power Generation

![World Wind Energy - Total Installed Capacity (MW) and Prediction 1997-2010](image)

Fig. 103: World-Wide Wind Power Generation.
There has been increasing world-wide interest in wind power generation as shown in Fig. 103. The amount of power generated using wind-power has grown from 7.5 Giga-Watts in 1997 to 74 Giga-Watts in 2006 with further increases occurring at the rate of a doubling of generation every three to four years. It is estimated that 12 percent of the world’s electricity needs will be supplied by wind-power in 2020. The leading wind power producers in the world are Germany and Spain, followed by the United States, according to the pie chart shown in Fig. 104.158. There has been a particularly strong growth in wind power generation in the U.S. as shown in Fig. 104. China is also aggressively pursuing wind-power generation. China plans to invest $700 Billion until 2020 in renewable energy projects. A Chinese company, Huadian Power International Corporation, has received approval to build two wind power projects with a combined capacity of 147 Mega-Watts. In addition, an Indian company, Suzlon Energy, has become the world’s eighth largest producer of wind turbine generators.159 Companies have also targeted wind-power as an important growth segment in the future. The most prominent is the General Electric Company with their “ecoimagination” initiative.160 The Swiss company ABB is in neck-to-neck competition with GE for this market.

A typical wind-power generator is illustrated in Fig. 105. The energy produced by the rotation of the blades is used to generate three-phase AC power. However, the frequency of the generated power varies widely due to changes in the wind speed. In order to deliver constant frequency power (50-Hz or 60-Hz) to the power grid with a well-regulated voltage, it is necessary to first rectify the generated power to produce a DC voltage across a capacitor, and then use IGBTs in an inverter stage to generate the desired AC output power at constant frequency and voltage. Before the availability of IGBTs, inverters were made using thyristors.
EDN magazine states\textsuperscript{161}: “Such devices handle kiloamp-level currents at several kilovolts, and progress within this (IGBT) technology has made the biggest single contribution to wind-turbine advances over the past several decades.” Replacement of thyristors with IGBTs enables reduction of the size and weight of the power electronics allowing its location in the gantry crane of the windmill. With IGBTs, pulse-width-modulation (PWM) is possible allowing control of real and reactive power. It is now well established that the IGBT is the most suitable power semiconductor device for wind power generation applications\textsuperscript{162}. The IGBT based inverters eliminate the need for the heavy and unreliable gear-box that had to be located in the gantry. A good discussion of the advantages of the IGBT-based PWM inverters can be found in many papers in the literature\textsuperscript{163}.

Many manufacturers have IGBT products that are targeted specifically for the wind-power market. Examples are the Mitsubishi Electric Company’s ‘Mega-Power Dual Series IGBTs’, Infineon’s ‘EconoDual 3’, Powerex ‘CM450DX’, Fuji Electric ‘2MB1600VXA’, etc. Recently, Xinjiang Goldwind Science and Technology Co., Ltd., signed a license agreement with Infineon to produce IGBTs for use in AC-converters for wind turbines\textsuperscript{164}. In addition, Infineon has announced opening a new facility in China called ‘Infineon Integrated Circuits (Beijing) Company’ to manufacture IGBT stacks\textsuperscript{165}.

4.16.2 Solar Power Generation

As mentioned earlier, solar power has a large potential to provide the electricity needs of the world’s burgeoning population. However, in 2008 solar-power supplied less than 0.02% of the world's total energy supply. In a solar or photovoltaic cell, the incident sunlight is converted into an electrical current using the photoelectric effect within semiconductors as shown in Fig. 106.
The Insulated Gate Bipolar Transistor

The typical silicon P-N junction produces the current at a DC voltage of about 0.8 volts. Many such junctions must be placed in series and parallel to create a solar panel with sufficient power generation capability for use in homes or power delivery systems. Typical solar panels may produce hundreds of watts of power at a DC voltage of about 300 volts.

![Diagram of Solar Cell Principle](image1)

**Fig. 106: The Solar Cell Principle.**

The DC voltage produced by the solar array must be converted into a desired well regulated AC power by using an IGBT-based inverter. A typical circuit for converting the DC solar power to the 50 or 60 Hz AC power is shown in Fig. 107[166]. Chou from International Rectifier states [167]: “For solar inverter applications, it is well known that insulated-gate-bipolar-transistors (IGBTs) offer benefits compared to other types of power devices, like high-current-carrying capability, gate control using voltage instead of current, and the ability to match the co-pack diode with the IGBT.” IGBTs deliver low conduction and switching losses resulting in high inverter efficiency. Many companies have developed IGBT products specifically targeted for the solar inverter application. Some examples of IGBT products tailored for solar inverter applications are the Microsemi ‘APTGV30H60T3G’, International Rectifier ‘IRG4PC40UDBF’, Infineon ‘EconoDual IGBT’, etc. A large number of IGBT suppliers have also recently been set up in China due to anticipated market growth[168]. Infineon has announced opening a new facility

![Diagram of Photovoltaic Inverter](image2)

**Fig. 107: Photovoltaic Inverter.**
in China called ‘Infineon Integrated Circuits (Beijing) Company’ to manufacture IGBT stacks\textsuperscript{165} for use in solar inverters.

4.16.3 Ocean-Wave Power Generation

It is estimated that 400 Giga-Watts of power can be generated from wave energy\textsuperscript{169}. Two examples of wave powered generators are shown in Fig. 108. The world’s first commercial scale, sea-based, wave energy generation system was installed in Clydebank, Scotland. This system, shown in Fig. 108(a) named OSPREY for ‘Ocean Swell Powered Renewable Energy’, is capable of generating 2 Mega-Watts of power to support more than 1000 homes. Ocean’s natural swells are directed into the structure to form an oscillating column of water. As the water column rises and falls, air is pushed out and sucked in through the top of the structure turning a turbine to generate the electricity.

![Fig. 108: Wave Power: (a) Osprey Structure, (b) Pelamis Sea Monster.](image)

![Fig. 109: Osprey Power Generation System.](image)
The OSPREY power generation system is illustrated in Fig. 109. The wave energy is first converted into wind energy which produces kinetic energy in the turbine used to produce the electrical energy sent to the power grid. The first OSPREY was located 300 meters off-shore north of Dounreay in 14.5 meters of water. The OSPREY’s design has four 500-kW rated Well’s turbines. The author states 169: “This approach favoured the use of an IGBT voltage source induction generator system due to the control/performance advantages and the ruggedness and reliability of an induction machine... The power electronics plays a vital role in the system. It not only gives the opportunity to control the generator torque profile to ensure that optimum energy recovery is achieved for but also affords the luxury of being able to act and react to changes in environmental conditions.”

4.17 Mass Energy Storage Sector

Mass energy storage systems are needed in power generation and distribution networks for system stabilization and load compensation as illustrated in Fig. 110170. This can be provided by ‘Superconductive Magnetic Energy Storage (SMES)’ systems. For power system stabilization, the SMES unit is placed close to the power generation source while for load compensation, the SMES unit is placed close to the factory or railway sub-station. In the SMES, energy is stored as a magnetic field produced by a DC current flowing through a superconducting coil. The superconducting coil must be cooled to below the critical temperature of the wires. The SMES...
system consists of the superconducting coil, the power conditioning system, and the refrigeration system. The power conditioning system converts input AC power to the DC current in the superconducting coils to store energy. It also converts the stored DC current into an AC power fed to the grid or the local load. NEDO (New Energy and Industrial Development Organization) of the Chubu Electric Power Company in Japan has installed and operated a 10 Mega-Watt SMES system. A SMES unit, made by the Sharp Corporation, capable of storing 10-Mega-Watts of power is shown in Fig. 111. The superconducting coil is cooled to -269°C in this SMES design.

Fig. 111: Superconductive Magnetic Energy Storage Unit.

Fig. 112: SMES Power Circuit.
The typical power circuit\textsuperscript{172} used for the SMES system is shown in Fig. 112. In this example the AC power from the wind generator is converted to DC power using the IGBT-based voltage source converter and then fed to the superconducting coil using the DC-DC chopper circuit containing IGBTs. The authors state: "Transient stability of the power system for symmetrical and unsymmetrical faults is analyzed and it is shown that the SMES unit with the proposed controller can improve the dynamic performance of wind generator significantly." Quench detection and protection is a critical part of the SMES unit. During a quench sequence, the stored electrical energy in the SMES is converted into heat. This function can be performed by using IGBTs\textsuperscript{173}.

4.18 Other IGBT Applications

There are numerous other applications for the IGBT that do not fit into the many categories used above to describe their usage in various sectors of the economy. Some of these applications are highlighted here.

4.18.1 Power Factor Correction

![Power Factor Correction Circuit](Image)

Enormous energy savings can be derived on the consumption side of improvement of the power factor for products such as digital TVs, DVD players, audio equipment, personal computers, printers, air-conditioners, microwaves, cooktops, electronic ballasts for lights, etc. Power factor is defined by the phase difference between the voltage and current waveforms in a load. Most loads tend to have lagging power factor due to the inductive energy storage elements. There has
been a global movement towards improving the power factor to make it close to unity for most electronic products. The U.S. Energy Star program mandates that standard model external power supplies with output power of more than 49 watts should have a power factor of better than 0.87, while internal power supplies should have a power factor better than 0.9 at rated output\textsuperscript{174}. Similar requirements have been mandated in European countries by the European Directive EN61000-3-2.

A typical power factor correction (PFC) circuit is illustrated in Fig. 113\textsuperscript{175}. The voltage and current at the load are sensed and the output of the sensors used to control the switching of the IGBT. The PFC module is compact, simple to manufacture and has low cost due to integration of the IGBT, fast recovery diode, and control circuit in a single package\textsuperscript{176}. IGBTs have been optimized to obtain the best efficiency in the PFC circuit.

4.18.2 Fractional Horse-Power Motor Drives

Fraction horse-power (FHP) motor drives are needed for control of small motors that are prevalent in most electronic systems for cooling the semiconductor chips. A cooling fan assembly for a microprocessor in a personal computer is shown in Fig. 114. It is advantageous to create a monolithic FHP drive to reduce the size and cost. This became cost effective with the discovery that high voltage lateral power device structures could be built in dielectrically isolated substrates with the RESURF principle\textsuperscript{177}. Using dielectric isolation, it became possible to utilize multiple bipolar devices, such as the IGBT and PiN rectifier, to create an H-bridge circuit within a single chip.

The basic circuit\textsuperscript{178} for the monolithic FHP drive is illustrated in Fig. 115. The circuit contains six IGBTs and six fly-back rectifiers in an H-bridge configuration together with low-side and high-side drivers. In addition, under-voltage and over-voltage protection circuits are on
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the chip with a thermal shut-down capability. The monolithic integration of the CMOS control circuits, the bipolar sense circuits, and the power devices is accomplished using silicon-on-insulator technology. This technology meets the qualifications of a ‘Smart Power Technology’\(^{179}\). The same type of chip can also be used for driving small pumps for control of liquids.

Fig. 113: Monolithic Fractional Horse-Power Drive.

### 4.18.3 Solid State Circuit Breakers

Mechanical circuit breakers are commonly used to protect electrical and electronic gear in consumer, industrial, aerospace and other areas. Mechanical circuit breakers need many milliseconds before they can be turned off by extinguishing an arc that developed across the points, and they must be manually reset after tripping. Electronic circuit breakers (ECB) have the advantages of a much faster response time of microseconds, fault current limiting capability, improved repeatability, and higher reliability. Typical circuit breakers are shown in Fig. 116(a)
for the lower power levels in homes and industries, and in Fig. 117(b) for high power levels needed in aircraft and naval applications.

An electronic circuit breaker relies up on a high voltage semiconductor switch to interrupt the fault current\textsuperscript{180}. The authors state: “The main circuit response to the state of current continuity of the whole system is by the core component IGBT... After considering the mode of control, switch response time, price, and on-state losses, IGBT is a best choice.” The best circuit topology for the electronic circuit breaker is shown in Fig. 117 with an IGBT and four diodes. With this topology, fault currents can be interrupted in both half cycles of the AC power flow to the load. IGBT based circuit breakers for both AC and DC power delivery in Naval vessels have also been developed\textsuperscript{181}. Circuit breakers are also required in high power transmission systems. As discussed previously in section 4.16, it is preferable to use DC voltage for long distance power transmission. This is achieved with voltage source converters based up on IGBTs as illustrated in Fig. 118. In addition, the DC circuit breaker function is accomplished by using IGBTs in the configuration shown in this figure on the right hand side\textsuperscript{182}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig117.png}
\caption{IGBT-Based Solid State Circuit Breaker.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig118.png}
\caption{Circuit Breakers for HVDC installations.}
\end{figure}
4.18.4 Gas Engine Cogeneration

Gas engine cogeneration systems (GES) are being utilized in homes, factories, and office buildings as distributed power generators. A typical motor-generator set is shown in Fig. 119 for use in homes. It consists of a gas engine, a synchronous generator, a rectifier stage and an inverter stage. The generated power is fed through a rectifier stage to create a DC voltage bus across a capacitor. An IGBT-based inverter stage is then used to produce the desired well regulated AC power for the home, office, or industry as shown in Fig. 120. An overall efficiency of more than 90 percent is possible using the IGBTs. Power factor control was also possible by replacing the thyristors shown in the rectifier stage with IGBTs. These types of generators can be used in homes under emergencies such as loss of power due to hurricanes. Typical examples of commercially available GES units are shown in Fig. 121.
4.18.5 Food Processing and Water Purification

Fig. 122: PEF Units: (a) Diversified Technologies Inc.; (b) SteriBeam Systems

Fig. 123: Circuit for PEF Sterilization Unit.
High voltage pulsed electric fields are increasing being applied for non-thermal food processing. Traditional thermal pasteurization that kills bacteria also degrades color, flavor, texture and nutrients in the food. Pulsed electric fields (PEF) of short duration (seconds) can be used instead for pasteurization leaving the quality of the food preserved\textsuperscript{184}. PEF equipment requirements are: (a) an electric field strength of 35 kV/cm; (b) repetition rate of 0-10,000 pps, (c) time duration of 1-20 microseconds; and (d) rise and fall times of less than 1 microsecond. Two typical PEF units used to sterilize powders, juices, etc., are shown in Fig. 122. These units can also be used for water purification while eliminating chemicals such as chlorine.

The circuit diagram for the PEF unit is shown in Fig. 123. A DC bus voltage is generated across a capacitor. IGBT modules are used to form an H-bridge configuration that drives the primary side of the transformer. The transformer steps up the voltage by a factor of 12-times. The IGBT inverter must be capable of handling 720-A of current. The author’s state: “The homogeneous transistors with features of high input impedance, high switching speed, and automatic current sharing are used in the IGBT module.”

### 4.18.6 Oil Extraction

As the petroleum industry matures, it must locate and extract oil from deeper and deeper reservoirs under the surface of the earth. The extraction of oil from deep underground, using oil wells like the one shown in Fig. 124, is difficult due to high viscosity and inclusion of asphalt. The viscosity can be reduced by either irrigating with hot water, addition of chemicals, or by electric heating of the pipelines. Electric heating technology is widely used by the oil industry because of its low cost\textsuperscript{185}. A single phase AC source at 40-100 Hz is supplied to the well wall to provide resistive heating. The basic set up for heating the oil pipe is illustrated in Fig. 125. The heating loop consists of the oil pipe and heater at the bottom of the well. When current flows through the loop, it not only increases the temperature at the bottom of the well but along the pipe due to the resistance of its walls.
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Fig. 125: Oil Well Pipeline Heating Unit.

Fig. 126: Oil Well Heating System.
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The circuit diagram for the oil-well heating system is shown in Fig. 126. The 50-Hz, 380-V, three-phase, AC power is converted to a DC bus by the rectifier stage and then inverted using the IGBTs to variable frequency ranging from 40-100 Hz. The heating efficiency is increased by 50 percent with this approach. The authors state: “The set has advantages of small volume and light weight because of IGBT in the inverter system...The system has been used to coagulated oil extraction in an oil extraction factory, Liaohe Oil Fields in China from December 2000 and has been running well.”

4.18.7 High Energy Particle Physics

To explore high energy physics at the Terascale, the SLAC National Accelerator Laboratory, shown in Fig. 127, has proposed a International Linear Collider. This electron-positron collider is about 31 km in length with a center-of-mass energy of 500 GeV upgradeable to 1 TeV. The particle acceleration is achieved by using the Marx modulator which is constructed using IGBTs as shown in Fig. 128. The authors state: “Driven by the continual evolution in performance and characteristics since its introduction in the early 1990s, the IGBT has become
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the device of choice for a wide range of medium and high voltage applications”. The 120-kV klystron design was therefore implemented using commercially available 6.5-kV IGBTs\textsuperscript{187}. The IGBT is also used at SLAC for construction of the 3.3 GeV electron beam deflection system\textsuperscript{188}.

4.18.8 Copy and Printing Machines

Fig. 129: (a) Copy Machine; (b) Laser Printer; (c) Facsimile Machine

The fixing process for the toner in copy machines, laser printers, facsimile machines, data recorders, and scanners (such those shown in Fig. 129) requires transfer of toner from the rolling drum to the printing paper with heat and pressure. Radiant heating with halogen lamps was used for this process in the past. However, nearly 90 percent of the printing energy is consumed by this operation. The efficiency can be improved by using the induction heating approach leading to reduction of the size of the printing devices.
A cross section of the toner fixing roller for a copier or printer is illustrated in Fig. 130. The induction heating coil is located concentrically inside the fixing roller. The high frequency inverter required to feed the inductive energy into the heating coil is built using IGBTs as shown in Fig. 131. The author’s state: “The actual high efficiency of more than 94 percent of the series resonant ZCS-PDM high frequency inverter for IH roller in copy and printing machines has been observed for all the output AC power regulation ranges from 50 to 1200 W.”

4.18.9 NASA Space Shuttle

The Space Shuttle is arguably one of the most successful projects developed at NASA. Many years ago, the Propulsion Laboratory at the NASA George C. Marshall Space Flight Center (MSFC) initiated the replacement of hydraulics for spacecraft gimballing systems with electromechanical
The report states: “As early as 1972, NASA engineers expressed concern over the space shuttle’s hydraulic system due to difficult maintainability and some minor inefficiencies. In 1987, the Control Mechanisms and Propellant Delivery Branch at MSFC designed and tested an electromechanical propellant valve actuator applicable to the space shuttle main engine. It performed as well as, and in some areas better than, its hydraulic counterpart.” A three-phase, six transistor, six step, bridge network was used. The switches were insulated gate bipolar transistors rated at 500-V and 200-A.

Fig. 133: The Space Shuttle Propulsion Control System

Fig. 134: The Space Shuttle Hydraulic Actuator.
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A schematic diagram of the propulsion system in the space shuttle is shown in Fig. 133. The reusable rocket engine design for the Space Shuttle requires high performance and reliability. This can be achieved with fault tolerant operation to maximize engine life. The major elements of the propulsion system are a tank pressure coordinator, a fuel utilization coordinator, and a thrust vector coordinator. The hydraulic system is illustrated in Fig. 134. The major concern with this method is maintenance and reliability. The electromechanical actuator requires control of a six-pole permanent magnet motor. The IGBT based motor drive is shown in Fig. 135. It provides the drive for a 13.6 hp motor operated at a maximum speed of 2759 rpm. The inverter is based on 600-V, 400-A IGBTs.

5 Social Impact

In 2009, Time Magazine published an article on the impact of energy efficiency on the U.S. economy. The article states: “This may sound too good to be true but the U.S. has a renewable energy source that is perfectly clean, remarkably cheap, surprisingly abundant, and immediately available... This miracle juice goes by the distinctly boring name of energy efficiency.” Steven Chu, Energy Secretary, has stated: “I cannot impress upon you how important energy efficiency is.” The Time magazine article concludes that energy efficiency is the only cost effective ‘energy source’ that addresses global warming, energy independence, and volatile prices. A strong argument for improving energy efficiency is also made by Lovins and Cohen in their book ‘Climate Capitalism’. Chapter 2 in the book is titled “Energy Efficiency: Low-Hanging Fruit that Grows Back”. They quote an energy saving opportunity of $130 Billion annually from energy savings according to a 2007 McKinsey study. Small businesses consume half the electricity in the U.S. and can save 20 to 30 percent on their energy bills by using energy efficient appliances.

Since the 1980s, IGBTs have played a critical role in the development of products with improved energy efficiency. This section highlights specific examples of the energy savings derived by using IGBT enabled products in the transportation, consumer, industrial, and lighting
sectors of the economy. Based upon the energy savings derived with the IGBT enabled appliances, it is possible to compute the cost savings to consumers. In addition, the reduced energy consumption eliminates the need for generation of electricity from fossil fuel powered generation plants. This reduces the investment in generation capacity by the utility industry and eliminates a very large amount of carbon emissions.

5.1 Economic Benefits Derived from IGBTs

The economic benefit derived by consumers using IGBT enabled products is described here. Three examples are provided to quantify the enormous cost savings gained by consumers over the last 20 years since the wide-spread commercial availability of the IGBT. These examples cover the transportation, consumer, industrial, and lighting sectors of the economy.

5.1.1 Gasoline Savings from Electronic Ignition Systems

Most cars and trucks around the globe rely upon the gasoline powered internal combustion engine for powering the vehicles. As discussed in section 4.1, until the late 1980s, the ignition system for the internal combustion engine used in gasoline powered vehicles was based up on using a mechanical distributor for controlling the timing for the spark plugs. This method was prone to poor control and failure from wear out of the contacts. The availability of the IGBT enabled introduction of reliable distributor-less electronic ignition systems in the late 1980s with no moving parts. The article states: "A primary constraint to the adoption of electronics innovations was the ability to make components durable enough to withstand the heat and vibration factors of an automobile in daily use". The IGBT was the first power switch with sufficient high temperature operation and ruggedness attributes to allow cost effective and reliable implementation of the distributor-less electronic ignition system.

![Fuel Consumption in the United States](image-url)
The Insulated Gate Bipolar Transistor

It is generally acknowledged that the distributor-less electronic ignition system reduces maintenance costs while allowing more precise control of the timing for the spark plugs which improves fuel efficiency, reduces emissions, and increases the overall power of a car. Electronic ignition systems have the advantage of operating at a higher voltage than possible with mechanic points. The larger voltage can be applied across a wider spark gap leading to a longer and broader spark. The larger spark volume allows a leaner fuel mixture that leads to better fuel efficiency and a smooth running engine. The improvements in fuel efficiency derived from using the electronic ignition systems has been documented to range from 2 to 4 miles per gallon of fuel. A UNDP study on the impact of electronic ignition systems has established a 10 percent improvement in fuel economy while reducing environmental pollution. Based up on the available data, it is reasonable to assume that the introduction of the electronic ignition system using IGCTs has produced fuel savings of at least 10 percent.

The fuel used for transportation in the U.S. is mainly gasoline (62 percent) as shown in Fig. 136. Gasoline is the main fuel used for powering automobiles and trucks which constitute 60 percent of the fuel demand as shown on the right-hand-side of the figure. These vehicles are based upon internal combustion engines that now utilize electronic ignition systems utilizing IGCTs to control the voltage delivered to the spark plug.

<table>
<thead>
<tr>
<th>Year</th>
<th>Number registered (thousands)</th>
<th>Vehicle-miles traveled (millions)</th>
<th>Fuel consumed (million gallons)</th>
<th>Average miles traveled per gallon</th>
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<tbody>
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<td>1960</td>
<td>61,671</td>
<td>99,244</td>
<td>61,671</td>
<td>14.3</td>
</tr>
<tr>
<td>1970</td>
<td>121,601</td>
<td>156,766</td>
<td>69,568</td>
<td>13.5</td>
</tr>
<tr>
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<td>121,580</td>
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<td>12.3</td>
</tr>
</tbody>
</table>

Fig. 137: Gasoline Consumption in the United States.

The fuel consumption in the U.S. and around the world has been growing over the years. The gasoline fuel used by cars and trucks in the United States is tabulated in Fig. 137. Similary data is available at the referenced link for total gasoline consumption around the world. The
gasoline consumption data is plotted in Fig. 138. The United States consumes about one-quarter of the total gasoline consumption around the world. The introduction of the electronic ignition system in the late 1980s due to the availability of IGBTs has resulted in a gasoline savings of at least 10 percent. The gasoline savings from using the electronic ignition system enabled by IGBTs will therefore be computed from the data in Fig. 138 using a conservative estimate of 10 percent of the gasoline consumption. This gasoline savings for the United States and the World is provided in Fig. 139.

Fig. 138: Gasoline Consumption in the United States and the World.

Fig. 139: Gasoline Savings in the United States and the World from using IGBT-enabled Electronic Ignition Systems.
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From the data shown in Fig. 138 and Fig. 139, the cumulative impact of the IGBT-based electronic ignition systems can be determined. The cumulative savings in gasoline for the United States for the 20-year period between 1990 and 2010 is found to be 326 Billion gallons. The cumulative savings in gasoline for the entire world for the 20-year period between 1990 and 2010 is found to be 1146 Billion gallons. This reduction in fuel use has the obvious benefit to consumers by decreasing their expenditures.

In order to determine the economic benefit to consumers from the gasoline savings, it is necessary to use the price for gasoline which has varied over a large range during the 20-year period from 1990 to 2010. The price for regular unleaded gasoline in the United States has been documented by the Energy Information Administration\textsuperscript{204}. Although the price for gasoline varies across the country and is dependent on the seasons, the Energy Information Administration has published the national average price for regular unleaded gasoline between 1949 and 2008 normalized to year 2000 dollars. This data is graphically represented in Fig. 140. It can be observed that there has been a steady increase in the price for gasoline from about $1.30 in the 1990 to about $2.90 in 2010. There was a sharp spike in the price of gasoline in the United States to nearly $4.00 in 2008. The price of gasoline in Europe is three to four times the price of gasoline in the United States\textsuperscript{205}. Prices have averaged $8.10 per gallon over the period from 2000 to 2005. For purposes of the analysis here, it will be assumed that the price of gasoline in the rest of the world (i.e. Non-US regions) is 3.5-times the average price for unleaded regular gasoline in the U.S. shown in Fig. 140.

Fig. 140: Average Price for Unleaded Regular Gasoline in the United States.
Fig. 141: Annual Gasoline Cost Savings for Consumers in the United States.

Fig. 142: Annual Global (Non-U.S.) Gasoline Cost Savings for Consumers.
The gasoline cost savings for U.S. consumers from the introduction of the IGBT-enabled electronic ignition systems is plotted in Fig. 141. The cost savings have grown from the range of $15 Billion per year to $50 Billion per year as the consumption and price for gasoline has increased over the years. The cumulative cost savings for U.S. consumers adds up to $570 Billion. Since much of the gasoline in the U.S. is imported, this savings also helps reduce the balance of trade for the nation.

The reduced gasoline consumption obtained by using IGBT-enabled electronic ignition systems also benefits consumers from around the world. The gasoline cost savings for non-U.S. consumers from the introduction of the IGBT-enabled electronic ignition systems is plotted in Fig. 142. The cost savings have grown from the range of $150 Billion per year to $590 Billion per year as the consumption and price for gasoline has increased over the years. The cumulative cost savings for non-U.S. consumers adds up to $5,080 Billion ($5.080 Trillion). This has had an important impact on the economies of nations around the world.

5.1.2 Electricity Savings from Adjustable Speed Motor Drives

According to the U.S. Department of Energy and the Electric Power Research Institute, two-thirds of the electricity in the United States is used to run motors in consumer and industrial applications. Motors are used in industrial and consumer sectors for (a) food production; (b) machining; (c) packaging; (d) milling, (e) oil and gas production; (f) water pumping; (g) heating.
and cooling of building and residences; (h) refrigeration; (i) irrigation, etc. As discussed in section 4.2, induction motors were commonly used with dampers in the past resulting in poor efficiency. A major improvement in efficiency can be derived by replacing this approach with an adjustable or variable speed drive for motors. A typical example is illustrated in Fig. 143 for a centrifugal fan drive. At full-load, the efficiency of the old method is satisfactory. However, for typical conditions below full-load, the variable speed drive provides an improvement in efficiency of at least 40 percent. Mayflower Vehicle Systems, manufacturer of body panels for Aston-Martin and MGF cars, states that running costs have been reduced by 87.9 percent by using ABB variable speed drives. Washington State University states that almost 70 percent reduction in pumping energy can be obtained by using adjustable speed drives. A very detailed report documenting energy savings from adjustable speed drives for motors has been prepared by Arthur D. Little, Inc., for the U.S. Department of Energy. Based upon these studies and reports, an efficiency improvement of 40 percent will be assumed for the analysis in this section.

Typical energy loads in a residential and commercial building are shown in Fig. 144. Air-conditioning and refrigeration account for a major portion of the load. The electricity needs for the United States are met by power generation from a variety of sources as shown in Fig. 145. According to data published by the U.S. Energy Information Administration, the electricity consumption in the United States has been steadily increasing, as shown in Fig. 145. Fossil fuel is a dominant source for electricity production because of the availability of large amounts of coal and natural gas at a low cost. The total electricity needs for the United States has grown from 2300 Terra-Watt-Hours in 1980 to 4100 Terra-Watt-Hours in 2009.

![Fig. 144: Typical Energy Loads: (a) Residential; (b) Commercial.](image-url)
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The electrical energy savings obtained by replacing the old induction motor drives with modern IGBT-based adjustable speed drives can be obtained by taking 40 percent of the electricity consumption by motor in the United States, which two-thirds of the total electricity production shown in Fig. 145. This energy savings has been plotted in Fig. 146 in Giga-Watts by dividing the energy per year in Terra-Watt-hours shown in Fig. 145 by a factor of \((365 \times 24 = 8760\) hours) and dividing by a factor of \(1000\) to convert Terra-Watts to Giga-Watts, and then taking two-thirds of this value. It can be concluded that an electrical energy savings of between 90 and 130 Giga-Watts has been saved during the years from 1990 to 2010. The reduction of electrical energy needs produced by this improvement in electrical efficiency allows the U.S. utility industry to avoid building more coal-fired power plants. Each coal-fired power plant produces about 1 Giga-Watt of power and costs $3 Billion.\(^{214}\) By avoiding the construction of 130 coal-fired power plants, the utility industry in the United States has saved $380 Billion due to the availability of the high-efficiency IGBT-based adjustable speed motor drives.

The reduced electricity use by availability of the IGBT-based adjustable speed drives is also beneficial to consumers due to their reduced electricity bill. The average electricity cost for consumers across the United States has been published by the U.S. Energy Information Administration.\(^{215}\) Their average electricity cost is 11.09 cents per kWh for residential customers, 6.72 cents per kWh for industrial customers, and 10.68 cents per kWh for transportation customers. The average electricity cost across all the sectors is 10 cents per kWh. This value will therefore be used when computing the cost benefit derived by using IGBT-based variable speed motor drives.

![Fig. 145: Electricity Production in the United States.](image)
Fig. 146: Electrical Power Savings in the United States from using IGBT-enabled Adjustable Speed Motor Drives.

Fig. 147: Electricity Cost Savings in the United States from using IGBT-enabled Adjustable Speed Motor Drives.
The electricity cost savings for customers in the United States due to smaller energy consumption resulting from IGBT-enabled adjustable speed motor drives is shown in Fig. 147. These values were obtained by taking the electrical energy savings shown in Fig. 146 and multiplying by a factor of $10^9$ to convert the data to kilo-Watts and by $(365*24)$ to obtain the annual energy savings in kWh. The energy savings in kWh was then multiplied by the cost of electricity ($0.10 per kWh) to obtain the annual cost savings. It can be observed from Fig. 147 that U.S. customers have derived a cost savings ranging from $80 Billion in 1990 to $110 Billion in 2010. The cumulative electricity cost savings for customers in the United States adds up to $2,069 Billion ($2.1 Trillion) over the 20-year period from 1990 to 2010.

As in the case of the United States, according to the International Energy Agency, the electrical energy consumption in the world has also been growing rapidly\textsuperscript{216} as shown in Fig. 148. The compelling benefits of electrical appliances and manufacturing technology have pushed the demand for electricity not only in the developed nations of Europe but also in the under-developed nations. The electricity consumption has increased from 500 Terra-Watt-Hours in 1945 to 19,500 Terra-Watt-Hours in 2010.

The penetration of IGBT-based adjustable speed motor drives in European countries is high due to strong desire for obtaining a good efficiency because of limited energy resources. Even in developing countries, such as China and India, IGBT-based adjustable speed motor drives have become popular. A large number of companies are manufacturing and marketing IGBT-based adjustable speed motor drives in these countries. In fact, the demand for IGBT-
based adjustable speed motor drives is so strong that Infineon is setting up a new manufacturing plant in Beijing for IGBT stack modules\textsuperscript{217}. The energy savings derived by using IGBT-based adjustable speed motor drives is shown in Fig. 149 using an improvement in efficiency of 40 percent and two-thirds of the electricity being used for motors. The cases of 100, 50, and 25 percent penetration rate for adjustable speed motor drives are provided in the chart. With the 100 percent penetration assumption, the electrical energy savings range from 350 and 600 Giga-Watts during the years from 1990 to 2010 resulting in the world’s utility industry saving $ 1,780 Billion ($ 1.78 Trillion) in power plant construction. With the 50 percent penetration assumption, the electrical energy savings range from 175 and 300 Giga-Watts during the years from 1990 to 2010 resulting in the world’s utility industry saving $ 890 Billion. With the 25 percent penetration assumption, the electrical energy savings range from 90 and 150 Giga-Watts during the years from 1990 to 2010 resulting in the world’s utility industry saving $ 445 Billion. Since the case of 25 percent penetration for the entire world is found to be close to that of the U.S. alone, it is most realistic to assume a penetration of 50 percent for the entire world.

![Fig. 149: Electrical Power Savings in the World from using IGBT-enabled Adjustable Speed Motor Drives.](image)

The cost of electricity for customers varies widely around the world\textsuperscript{218}. It is generally high in European countries where the citizens of Denmark, Germany, and Italy pay $ 0.43, $ 0.31, $ 0.37 per kWh, respectively. The price for electricity is slightly lower in Russia ($ 0.13 per kWh) and Finland ($ 0.07 per kWh). The prices also vary widely in Asian countries where the citizens of Philippines, Singapore, and Malaysia pay $ 0.16, $ 0.21, $ 0.074 per kWh,
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respectively. For the analysis in this section, an average price for electricity of $0.20 per kWh will be assumed.

The electricity cost savings for world-wide consumers due to smaller energy consumption resulting from IGBT-enabled adjustable speed motor drives is shown in Fig. 150. These values were obtained by taking the power savings shown in Fig. 149 for the three cases of penetration of adjustable speed motor drives. It can be observed from Fig. 150 that world-wide customers have derived a cost savings ranging from $600 Billion in 1990 to $1,040 Billion in 2010 if 100 percent penetration is assumed, from $300 Billion in 1990 to $520 Billion in 2010 if 50 percent penetration is assumed, and from $150 Billion in 1990 to $260 Billion in 2010 if 25 percent penetration is assumed. The cumulative electricity cost savings for world-wide customers adds up to $16.75 Trillion, $8.37 Trillion, and $4.19 Trillion over the period from 1990 to 2010 for the three penetration cases. Consequently, with a realistic penetration rate of 50 percent for the IGBT-based adjustable speed motor drives, people around the world have derived an enormous cost benefit of over $8 Trillion due to the IGBT-enabled adjustable speed motor drives. With a penetration of 50 percent, the analysis indicates huge room for further savings in energy as more IGBT-based adjustable speed motor drives are used in the future.

![Fig. 150: Electricity Cost Savings in the World from using IGBT-enabled Adjustable Speed Motor Drives.](image)

**5.1.3 Electricity Savings from Compact Florescent Lamps**

Lighting consumes about 22 percent of the electricity in the United States with similar levels in the rest of the world. There has been a world-wide movement towards replacing the
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incandescent bulbs due to their very poor efficiency (4 percent) for conversion of electric power into usable light. The most cost effective option for replacement of the incandescent lamp at present is the compact fluorescent lamp (CFL). A typical CFL consumes only 15 watts of power for producing the same amount of light when replacing a 60-Watt incandescent bulb. After a slow start in the 1990s, there has been a rapid growth in the sales of compact fluorescent lamps in the last decade around the world.

The sale of compact fluorescent lamps in the United States has been reported by various sources. Since 1999, the CFL sales have grown rapidly in the United States. Walmart has promoted the sale of CFLs by dropping prices and in November 2006 announced a goal of selling 100 million CFLs by the end of 2007, a target that was met by October 2007. Unfortunately, the sales for CFLs in the U.S. dropped by 25 percent from 2007 levels in 2008 and by 49% from 2007 levels in 2009. The data shown in Fig. 151 takes into account the recent decline in sales in 2008 and 2009.

![Fig. 151: Sales of Compact Fluorescent Lamps in the United States.](image-url)

For determining the power savings derived from CFLs, it is appropriate to use the total installed CFLs for each year. One assumption that could be made is that all the purchased CFLs have been used to replace incandescent bulbs. However, since the life of a CFL is about 10,000 hours, it can be used for only 5 years based upon being turned-on for 6 hours per day. It will be therefore be assumed that the CFLs purchased during any particular year will be first used to replace those purchased 5 years ago with the balance being used to replace incandescent lamps. The cumulative CFLs in use in the United States based upon this methodology are shown in Fig.
152. Even under this more conservative methodology, it can be seen that the cumulative CFLs in use in the United States have grown dramatically over the years.

Fig. 152: Total Compact Fluorescent Lamps in Use in the U.S.

Fig. 153: Power Savings from Compact Fluorescent Lamps in the United States.
The power savings derived by replacing 60 watt incandescent bulbs with compact fluorescent lamp can be computed by using the 45 watts power savings per bulb\(^2\). The power savings obtained from the installed CFLs shown in Fig. 152 is provided in Fig. 153. The power savings have grown from 0.45 Giga-Watts in 1999 to a maximum of 55.72 Giga-Watts in 2009. This has provided a cost savings of $167 Billion to the U.S. utility industry from avoiding the building of power plants.

The electricity cost savings for customers in the United States due to smaller energy consumption resulting from IGBT-enabled compact fluorescent lamps is shown in Fig. 154. These values were obtained by taking the electrical power savings shown in Fig. 153 and multiplying by a factor of \(10^6\) to convert the data to kilo-Watts and by \((365*6)\) to obtain the annual energy savings in kWh. This analysis assumes that each CFL is turned-on for 6 hours per day. The energy savings in kWh was then multiplied by the cost of electricity ($0.10 per kWh) to obtain the annual cost savings. It can be observed from Fig. 154 that U.S. customers have derived an annual cost savings ranging from $0.10 Billion in 1999 to $12.2 Billion in 2009. The cumulative electricity cost savings for customers in the United States adds up to $48.8 Billion over the 10-year period from 1999 to 2009. It is worth pointing out that 75 percent of the screw-in sockets for light bulbs in the United States still contained incandescent bulbs in 2010\(^2\). Although the adoption of compact fluorescent lamps in the United States has been adversely impacted in the last two years by the poor economy, there is a large room for obtaining energy and cost savings in the future with better education of the populace of the benefits of CFLs.

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Fig. 154: Electricity Cost Savings for Consumers from Compact Fluorescent Lamps in the United States.
In contrast, the adoption of compact fluorescent lamps in the rest of the world has been progressing monotonically. Worldwatch Institute states: “In the United States, CFLs accounted for more than 20 percent of sales in 2007. But other wealthy nations have shown much higher CFL use rates for quite some time, including 80 percent of households in Japan and 50 percent in Germany by 1996. Many developing countries have shown strong CFL market
share in recent years as well: 14 percent of sales in China in 2003 for instance and 17 percent in Brazil in 2002." Australia became the first country to ban the sale of incandescent bulbs in 2007. The European Union, Ireland and Canada have passed similar legislation. Worldwatch states: “In total, more than 40 countries have announced plans to follow suit.” Even India has launched a program\textsuperscript{223}, called Bachat Lamp Yojana (BLY), to replace the 400 million incandescent bulbs in use in the country with CFLs. In 2008, 199 million CFLs were sold in India.

The global sales of compact fluorescent lamps have been monotonically growing at an annual rate of 20 percent\textsuperscript{224} since the early 1990s as shown in Fig. 155. According to the Chinese GFL Lighting Technology Group, the production of CFLs is dominated by China with a market share of over 80 percent. This conclusion is affirmed by the data, shown in Fig. 156, published at the 2\textsuperscript{nd} International Forum on CFL Harmonization\textsuperscript{225}. The Worldwatch Institute states\textsuperscript{220}: “Between 2001 and 2006, production of compact fluorescent lamps (CFLs) in China, which account for roughly 85 percent of global output, tripled from 750 million to 2.4 billion units. The total number of CFLs in use globally nearly doubled between 2001 and 2003 alone, growing from an estimated 1.8 billion to 3.5 billion units.” The global sales of compact fluorescent lamps from 1990 to 2010 is shown in Fig. 157 based upon the data shown in the previous figures until 2004 and the information in the above references beyond that time until 2006. Since no data was found for the subsequent years, the sales are shown to be flattened in the interest of a conservative analysis despite the evidence of a continued growth of sales. It is estimated that each home in developed countries has more than 10 lamps with only 20 percent of the sockets in
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the United States filled with CFLs. In addition, CFLs are used in offices and factories to save energy and the labor cost of replacing incandescent lamps. CFLs have a ten-times longer life than incandescent bulbs making them attractive replacements in work-places.

![Fig. 158: Total Compact Fluorescent Lamps in Use Globally.](image1)

![Fig. 159: Power Savings from Compact Fluorescent Lamps in the World.](image2)
For determining the power savings derived from CFLs, it is appropriate to use the total installed CFLs for each year. One assumption that could be made is that all the purchased CFLs have been used to replace incandescent bulbs. Since the life of a CFL is about 10,000 hours, it can be used for about 5 years based upon being turned-on for 6 hours per day. It will be therefore be assumed that the CFLs purchased during any particular year will be first used to replace those purchased 5 years ago with the balance being used to replace incandescent lamps. The cumulative CFLs in use based upon this methodology are shown in Fig. 158. Even under this more conservative methodology, it can be seen that the cumulative CFLs in use in the World have grown dramatically over the years. The number of CFLs in use globally in Fig. 158 is consistent with published estimates.\(^{220}\)

The power savings derived by replacing a 60 watt incandescent bulb with a compact fluorescent lamp can be computed by using the 45 watts of power savings per bulb\(^{220}\). The power savings obtained from the world-wide installed CFLs (shown in Fig. 158) is provided in Fig. 159. The power savings have grown from 4.5 Giga-watts in 1999 to 634.5 Giga-Watts in 2009 resulting in the world’s utility industry saving $1.903 Billion ($1.90 Trillion) from avoiding installation of power generation plants.

The electricity cost savings for global customers due to smaller energy consumption resulting from IGBT-enabled compact fluorescent lamps is shown in Fig. 160. These values were obtained by taking the electrical power savings shown in Fig. 159 and multiplying by a factor of
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$10^6$ to convert the data to kilo-Watts and by $(365\times 6)$ to obtain the annual energy savings in kWh. This analysis assumes that each CFL is turned-on for 6 hours per day. The energy savings in kWh was then multiplied by the cost of electricity ($0.20$ per kWh) to obtain the annual cost savings. It can be observed from Fig. 160 that global customers have derived a cost savings ranging from $1.97$ Billion in 1990 to $277.9$ Billion in 2010. The cumulative electricity cost savings for global customers adds up to $1,829$ Billion ($1.89$ Trillion) over the 20-year period from 1990 to 2010.

5.2 Environmental Benefits Derived from IGBTs

![CO2 emissions world-wide](image)

![World temperature increase in °C](image)

Fig. 161: Global Carbon Dioxide Emissions and Rise in Temperature.

In the previous section, it has been demonstrated that enormous savings in gasoline and electricity consumption have been derived by using IGBT-enabled technology. This translates into a huge impact on the environment due to reduction of the pollutants in the air. The environmental impact of the IGBT on the environment will be highlighted in this section by using the three examples.

Among the pollutants, the emission of carbon dioxide has garnered the most attention during recent years due to its impact on global warming. Carbon dioxide is considered a greenhouse gas that allows trapping of solar infra-red radiation in the atmosphere producing global warming. The rising carbon dioxide emissions from 1991 to 2005 are shown in Fig. 161 with the attendant rise in global temperature\textsuperscript{226}. According to Professor D. Matthews from Concordia University Department of Geography, each ton of carbon dioxide added to the Earth’s atmosphere will raise the global temperature by $1.5 \times 10^{12}$ degrees (i.e. carbon dioxide emissions of one Trillion tons will raise the temperature by 1.5 °C)\textsuperscript{227}. It would, therefore, be prudent for society to reduce carbon dioxide emissions from all sources.
The per capita carbon dioxide emission for various countries is shown in Fig. 162. It can be observed that developed nations, such as the United States, Australia, and Canada, have a high per capita carbon dioxide emission rate of about 18 tons per year due to their high energy consumption. In contrast, under-developed nations, such as China and India, have a low per capita carbon dioxide emission rate of about 2 tons per year due to their low energy consumption. As the citizens of the under-developed countries strive to raise their living standards to rival those of the developed nations, it can be expected that the per capita carbon dioxide emission rate for these countries will also rise. Consequently, the present world-wide average per-capita carbon dioxide emission rate of 4 tons per year can be expected to burgeon to 20 tons per year. This would produce a significant acceleration of the rate of rise in global temperatures. There is consensus among the leading developed countries that global warming should be limited to a temperature rise of 2 °C. The annual global carbon dioxide emissions will have to be reduced from 28 Giga-tons in 2006 to 20 Giga-tons per year by the year 2050 to
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accomplish this goal while accommodating a rise in the global population from 6.4 Billion in 2007 to about 9.5 Billion in 2050\textsuperscript{226}. One solution to this problem is the improvement in the efficiency of automobiles and electrical appliances through the use of IGBT-enabled power electronics as described in previous sections.

The emission of green-house gasses occurs from all sectors of our economy. The distribution\textsuperscript{228}, shown in Fig. 163, indicates that one major part of the carbon dioxide emissions emanates from the transportation sector due to gasoline consumption. The other major source of carbon dioxide emissions emanates from the electric power generation due to electricity utilization in industrial processes and residential/commercial sources. The IGBT-enabled improvements in efficiency in all of these sectors of the economy have produced a major benefit to society in terms of reducing carbon dioxide emission as described below.

5.2.1 Automotive Electronic Ignition System

The emission of pollutants from gasoline powered vehicles has been well documented\textsuperscript{229}. In addition to carbon dioxide, the emissions from gasoline-powered vehicles include toxins that are known to be carcinogens. The U.S. Environmental Protection Agency states\textsuperscript{230}: “Motor vehicles emit several pollutants that EPA classified as known or probable human carcinogens. Benzene, for instance, is a known human carcinogen, while formaldehyde, acetaldehyde, 1,3-butadiene, and diesel particulate matter are probable human carcinogens.” In addition to these toxins, gasoline consumption produces the emission of carbon dioxide at the rate of 19.4 pounds per gallon\textsuperscript{231}.

Fig. 163: Green-House Gas Emissions by Economic Sectors.

The emission of green-house gases occurs from all sectors of our economy. The distribution\textsuperscript{228}, shown in Fig. 163, indicates that one major part of the carbon dioxide emissions emanates from the transportation sector due to gasoline consumption. The other major source of carbon dioxide emissions emanates from the electric power generation due to electricity utilization in industrial processes and residential/commercial sources. The IGBT-enabled improvements in efficiency in all of these sectors of the economy have produced a major benefit to society in terms of reducing carbon dioxide emission as described below.

5.2.1 Automotive Electronic Ignition System

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In section 5.1.1, it was demonstrated that the IGBT enabled introduction of cost effective and reliable electronic ignition systems for automobiles using the internal combustion engine. The electronic ignition system has improved the mileage derived from a gallon of gasoline by at least 10 percent resulting in reduction of gasoline consumption in the United States and around the world. The total reduction of gasoline consumption in the U.S. and the rest of the world between 1990 and 2010 is charted in Fig. 139. The reduction of carbon dioxide emissions in pounds per year due to this reduced gasoline consumption can be computed by multiplying the data in Fig. 139 by a factor of 19.4. The resulting annual reduction of carbon dioxide emission in the U.S. and around the world is shown in Fig. 164.

![Graph showing reduction in annual carbon dioxide emissions due to IGBT-based electronic ignition systems.](image)

**Fig. 164: Reduction in Annual Carbon Dioxide Emissions due to IGBT-based Electronic Ignition Systems.**

It can be seen from Fig. 164 that there has been a reduction of carbon dioxide emissions produced in the United States ranging from 254 Billion pounds per year in 1990 to a maximum of 346 Billion pounds per year in 2004. The cumulative reduction of carbon dioxide emissions produced in the United States due to the availability of IGBT-based electronic ignition systems is 6,323 Billion (6.32 Trillion) pounds over the twenty year period from 1990 to 2010. Similarly, it can be seen from Fig. 164 that there has been a reduction of carbon dioxide emissions produced by the world ranging from 920 Billion pounds per year in 1990 to a maximum of 1189 Billion pounds per year in 2007. The cumulative reduction of carbon dioxide emissions produced in the World due to the availability of IGBT-based electronic ignition systems is to 22.23 Trillion pounds (11.12 Billion tons) over the twenty year period from 1990 to 2010.
5.2.2 Adjustable Speed Motor Drives

In section 5.1.2, it was demonstrated that the IGBT enabled introduction of cost effective and reliable adjustable speed drives for motors. This enabled enhancement in the efficiency by at least 40 percent. The total reduction of electricity power consumption in the U.S. and the world between 1990 and 2010 is charted in Fig. 146 and Fig. 149. The reduction of carbon dioxide emissions in pounds per year due to this reduced electricity power consumption can be computed by multiplying the data in these figures by rate of carbon dioxide emission per kWh of electricity generated by typical power plants. The Environmental Protection Agency has analyzed the carbon dioxide emission from various types of power plants in the United States. Electricity is generated mostly (51 percent) from coal-fired power plants in the U.S as shown in Fig. 165. Unfortunately, the carbon dioxide emission from coal-fired power plants is the highest among the power generation options. The average carbon dioxide emission per kWh generated in the U.S. based upon all the fuel sources is 1.350 pounds according to the EPA as shown in Fig. 165. This value will therefore be used in the computation of carbon dioxide emission reductions in the United States resulting from IGBT-enabled adjustable speed motor drives.

The power savings achieved by using IGBT-enabled adjustable speed motor drives in the United States was shown in Fig. 146. The energy savings per year in kilo-Watt-hours (kWh) in the United States can be obtained by multiplying the power savings in Fig. 147 by (365*24*10^6). The reduction of carbon dioxide emissions due to the availability of IGBT-based adjustable speed motor drives obtained by multiplying the energy savings per year in kWh by 1.35 pounds/kWh is shown in Fig. 166. There has been a reduction of carbon dioxide emissions...
produced in the United States ranging from 1.1 Trillion pounds per year in 1990 to 1.5 Trillion pounds per year in 2010. The cumulative reduction of carbon dioxide emissions produced in the United States due to the availability of IGBT-based adjustable speed motor drives is 27.93 Trillion pounds over the twenty year period from 1990 to 2010.

![Graph showing reduction in carbon dioxide emissions in the United States from 1990 to 2010](image1)

Fig. 166: Reduction in Carbon Dioxide Emissions in the United States due to IGBT-Based Adjustable Speed Motor Drives.

The world-wide electricity generation is performed using a variety of fuels as shown in Fig. 167. It can be seen that coal is used for generating 41 percent of the world’s electricity.
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...demands. The carbon dioxide emissions from the world will therefore be computed by using (41/51)*1.35 = 1.1 pounds per kWh for the period from 1990 to 2010. However, according to the above reference, coal is used for generation of 79 percent of the electricity in the People’s Republic of China and 69 percent of the electricity in India. Since these two countries are the most aggressive in deploying new electricity generation capability due to their rapid economic growth, their electricity generation in the future will produce much higher levels of carbon dioxide emissions.

...power savings in the entire world by using IGBT-based adjustable speed motor drives were shown in Fig. 149 for three cases of penetration rate. As discussed in section 5.1.2, a worldwide penetration rate of 25 percent is inconsistent with the high penetration rates for adjustable speed drives in the United States, Japan, and Europe. Consequently, only the cases of 100 and 50 percent penetration rates will be considered here. The energy savings per year in the World in kWh can be obtained by multiplying the power savings in Fig. 149 by (365*24*10^6). The reduction of carbon dioxide emissions due to the availability of IGBT-base adjustable speed motor drives obtained by multiplying the energy savings per year in kWh by 1.10 pounds/kWh are shown in Fig. 168. It can be seen from Fig. 168 that there has been a reduction of carbon dioxide emissions produced in the World ranging from 1.65 Trillion pounds per year in 1990 to 2.86 Trillion pounds per year in 2010 for a 50 percent penetration rate. In this case, the cumulative reduction of carbon dioxide emissions produced in the World due to the availability of IGBT-based adjustable speed motor drives is 46.05 Trillion pounds over the twenty year...
period from 1990 to 2010. In the case of 100 percent penetration rate, a reduction of carbon dioxide emissions produced in the World increases to 5.72 Trillion pounds per year in 2010 indicating further room for benefits from the use of IGBT-base adjustable speed motor drives.

5.2.3 Compact Fluorescent Lamps

In section 5.1.3, it was demonstrated that the IGBT enabled introduction of cost effective and reliable compact fluorescent lamps. This allowed the replacement of incandescent bulbs to provide a typical power savings of 45 watts for a 60 watt bulb. Based upon this power savings, the total reduction of electricity power consumption in the U.S. and the world between 1990 and 2010 was charted in Fig. 153 and Fig. 159. The reduction of carbon dioxide emissions in pounds per year due to this reduced electricity power consumption can be computed by multiplying the data in these figures by rate of carbon dioxide emission per kWh of electricity generated by typical power plants. The Environmental Protection Agency has analyzed the carbon dioxide emission from various types of power plants. Electricity is generated mostly (51 percent) from Coal-fired power plants in the United States. Unfortunately, the carbon dioxide emission from coal-fired power plants is the highest among the power generation options. The average carbon dioxide emission per kWh generated in the U.S. is 1.350 pounds as shown in Fig. 165. This value will therefore be used in the computation of carbon dioxide emission reductions resulting from IGBT-enabled compact fluorescent lamps.

![Graph of Carbon Dioxide Emissions Reduction](image)

Fig. 169: Reduction in Annual Carbon Dioxide Emissions in the United States due to IGBT-Based Compact Fluorescent Lamps.
The power savings achieved by using IGBT-enabled compact fluorescent lamps in the United States was shown in Fig. 153. The energy savings per year in the United States can be obtained by multiplying the power savings in Fig. 153 by \((365 \times 6 \times 10^6)\) under the assumption that each CFL is used for 6 hours per day. The reduction of carbon dioxide emissions due to the availability of IGBT-based compact fluorescent lamps obtained by multiplying the energy savings per year in kWh by 1.35 pounds/kWh is shown in Fig. 169. There has been a reduction of carbon dioxide emissions produced in the United States ranging from 1.3 Billion pounds per year in 1999 to 165 Billion pounds per year in 2009. The cumulative reduction of carbon dioxide emissions produced in the United States due to the availability of IGBT-based adjustable speed motor drives is 659 Billion pounds over the ten year period from 1999 to 2009.

The power savings achieved by using IGBT-enabled compact fluorescent lamps in the World was shown in Fig. 159. The energy savings per year in the World can be obtained by multiplying the power savings in Fig. 159 by \((365 \times 6 \times 10^6)\) under the assumption that each CFL is used for 6 hours per day. The reduction of carbon dioxide emissions due to the availability of IGBT-based compact fluorescent lamps obtained by multiplying the energy savings per year in kWh by 1.10 pounds/kWh is shown in Fig. 170. There has been a reduction of carbon dioxide emissions produced in the World ranging from 0.01 Trillion pounds per year in 1990 to 1.53 Trillion pounds per year in 2010. The cumulative reduction of carbon dioxide emissions produced in the World due to the availability of IGBT-based compact fluorescent lamps is 10.06 Trillion pounds over the twenty year period from 1990 to 2010.
6 Summary and Conclusions

The IGBT was originally developed in the early 1980s for use in adjustable speed drives for heat pump applications. Soon after conception, it was apparent that this device had many of the attributes for an ideal power switch. This led to an immediate recognition of its wide-spread utility for enhancing the performance of many products within the General Electric Company, such as small and large appliances, advanced lighting products, locomotive drives, and even medical diagnostic tools. Once the IGBT became available from the G.E. Semiconductor Products Division, its commercial potential became apparent to all the leading power semiconductor manufacturers from around the world. A significant effort among Japanese power semiconductor manufacturers (Fuji Electric, Hitachi, Mitsubishi Electric, Toshiba, etc) led to rapid improvements in the current and voltage ratings allowing the IGBT to capture an increasing variety of applications over time. Today, the IGBT is ubiquitous in applications in all sectors of the economy including (a) the Consumer Sector, (b) the Industrial Sector, (c) the Transportation Sector, (d) the Lighting Sector, (e) the Power Transmission and Distribution Sector, (f) the Defense Sector, and (g) the burgeoning renewable Energy Sector. Numerous examples of IGBT-enabled applications in these sectors of the economy have been documented in this report with extensive references.

<table>
<thead>
<tr>
<th>IGBT Enabled Application</th>
<th>Cumulative Gasoline or Energy Savings</th>
<th>Consumer Cost Savings</th>
<th>Utility Cost Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>U.S.</td>
<td>World</td>
<td>U.S.</td>
</tr>
<tr>
<td>Electronic Ignition System</td>
<td>326 B gallons</td>
<td>1146 B gallons</td>
<td>$ 570 B</td>
</tr>
<tr>
<td>Adjustable Speed Motor Drive</td>
<td>20,690 TWh</td>
<td>41,870 TWh</td>
<td>$ 2,069 B</td>
</tr>
<tr>
<td>Compact Fluorescent Lamp</td>
<td>488 TWh</td>
<td>9,145 TWh</td>
<td>$ 49 B</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td>$ 2,688 B</td>
</tr>
</tbody>
</table>

Fig. 171: Gasoline, Electrical Energy, and Cost Savings for Consumers in the United States and Around the World.

The IGBT enables improvement in the efficiency of power delivery and energy management while reducing cost and size with high reliability. In this report, the social benefits brought about by the availability of IGBTs have been quantified by using three case studies: (a) the gasoline savings obtained by IGBT-enabled Electronic Ignition Systems, (b) the electricity...
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savings obtained by IGBT-enabled Adjustable Speed Motor Drives, and (c) the electricity savings obtained by IGBT-enabled Compact Fluorescent Lamps. The resulting enormous cost savings for consumers in the United States and around the World as summarized in Fig. 171. The case of 50 percent penetration rate for adjustable speed motor drives around the World was used here. The power savings enabled by the IGBT-based applications have also produced huge savings for the Utility Business by avoiding the construction of expensive electricity generating power plants. The cumulative cost savings for U.S. consumers over the 1990 to 2010 time frame adds up to $2.69 Trillion with additional savings for U.S. utilities of $551 Billion from not having to build power plants. The cumulative cost savings for World-Wide consumers over the 1990 to 2010 time frame adds up to $15.85 Trillion with additional savings for World-Wide utilities of $2.79 trillion from not having to build power plants.

<table>
<thead>
<tr>
<th>IGBT Enabled Application</th>
<th>Cumulative Gasoline or Energy Savings</th>
<th>Cumulative Carbon Dioxide Emission Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>U.S.</td>
<td>World</td>
</tr>
<tr>
<td>Electronic Ignition System</td>
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<tr>
<td>Compact Fluorescent Lamp</td>
<td>488 TWh</td>
<td>9,145 TWh</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 172: Carbon Dioxide Emission Reduction in the United States and Around the World.

The reduction of gasoline and electricity consumption due to IGBT-enabled Electronic ignition systems, adjustable speed motor drives, and compact fluorescent lamps has resulted in an enormous reduction in the emission of carbon dioxide. The cumulative reduction of carbon dioxide emissions over the period from 1990 to 2010 from these three application examples is provided in Fig. 172. The case of 50 percent penetration rate for adjustable speed motor drives around the World was used here. The cumulative carbon dioxide emissions reduction in the United States over the 1990 to 2010 time frame adds up to 34.91 Trillion pounds. The cumulative carbon dioxide emissions reduction in the World over the 1990 to 2010 time frame adds up to 78.35 Trillion pounds (39.2 Giga-Tons). The opportunity for reduction of carbon dioxide emissions from various sources has been recently analyzed\(^\text{35}\). The authors evaluated options for reduction of annual world-wide fossil-fuel carbon dioxide emissions from today’s 7.5
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Billion metric tons (or 15 Trillion pounds) per year. This value is consistent with the global fossil-fuel carbon emissions estimate by the Carbon Dioxide Information Analysis Center at Oak Ridge National Laboratory\textsuperscript{236}. Using this value, it can be concluded that the IGBT has enabled elimination of World-Wide carbon dioxide emissions equivalent to that produced by fossil-fuels in 5 years.

In the future, further reductions in carbon dioxide emissions will be achieved by increased generation of electricity from renewable energy sources, such as wind-power, solar-power, geothermal, etc. Time magazine has recently examined the renewable energy options\textsuperscript{237}. The article states: ‘‘President Obama’s latest target is to have 80% of U.S. energy needs supplied by clean sources by 2035...Meanwhile, the E.U. is working to double the share of energy derived from wind and other renewable sources, such as solar, geothermal, and biomass, to 20% by 2020.’’ All of these renewable energy generation options require conversion of the generated power into a well regulated 50 or 60 Hz AC power that can be distributed in the power grid. This is accomplished by using IGBT-based inverters as discussed in section 4.18. Consequently, IGBTs will play an ever increasing role in creating a sustainable global society with a high standard of living while reducing our impact on the environment and mitigating global warming.
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Professor Baliga obtained his Bachelor of Technology degree in 1969 from the Indian Institute of Technology, Madras, India. He was the recipient of the Philips India Medal and the Special Merit Medal (as Valedictorian) at I.I.T, Madras. He obtained his Masters and Ph.D. degrees from Rensselaer Polytechnic
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Institute, Troy NY, in 1971 and 1974, respectively. His thesis work involved Gallium Arsenide diffusion mechanisms and pioneering work on the growth of InAs and GaInAs layers using Organometallic CVD techniques. At R.P.I., he was the recipient of the IBM Fellowship in 1972 and the Allen B. Dumont Prize in 1974.

From 1974 to 1988, Dr. Baliga performed research and directed a group of 40 scientists at the General Electric Research and Development Center in Schenectady, NY, in the area of Power Semiconductor Devices and High Voltage Integrated Circuits. During this time, he pioneered the concept of MOS-Bipolar functional integration to create a new family of discrete devices. He is the inventor of the IGBT which is now in production by many International Semiconductor companies. This invention is widely used around the globe for air-conditioning, home appliance (washing machines, refrigerators, mixers, etc) control, factory automation (robotics), medical systems (CAT scanners, uninterruptible power supplies), and electric streetcars/bullet-trains, as well as for the drive-train in electric and hybrid-electric cars under development for reducing urban pollution. The U.S. Department of Energy has released a report that the variable speed motor drives enabled by IGBTs produce an energy savings of 2 quadrillion btus per year (equivalent to 70 Giga-Watts of power). The widespread adoption of Compact Fluorescent Lamps (CFLs) in place of incandescent lamps is producing an additional power savings of 30 Giga-Watts. The cumulative impact of these energy savings on the environment is a reduction in Carbon Dioxide emissions from Coal-Fired power plants by over One Trillion pounds per year. Most recently, the IGBT has enabled fabrication of very compact, lightweight, and inexpensive defibrillators used to resuscitate cardiac arrest victims. When installed in fire-trucks, paramedic vans, and on-board airlines, it is projected by the American Medical Association (AMA) to save 100,000 lives per year in the US. For this work, Scientific American Magazine named him one of the eight heroes of the semiconductor revolution in their 1997 special issue commemorating the Solid-State Century.

Dr. Baliga is also the originator of the concept of merging Schottky and p-n junction physics to create a new family of power rectifiers that are commercially available from various companies. In 1979, he theoretically demonstrated that the performance of power MOSFETs could be enhanced by several orders of magnitude by replacing silicon with other materials such as gallium arsenide and silicon carbide. This is forming the basis of a new generation of power devices in the 21st Century.

In August 1988, Dr. Baliga joined the faculty of the Department of Electrical and Computer Engineering at North Carolina State University, Raleigh, North Carolina, as a Full Professor. At NCSU, in 1991 he established an international center called the Power Semiconductor Research Center (PSRC) for research in the area of power semiconductor devices and high voltage integrated circuits, and has served as its Founding Director. His research interests include the modeling of novel device concepts, device fabrication technology, and the investigation of the impact of new materials, such as GaAs and Silicon Carbide, on power devices. In 1997, in recognition of his contributions to NCSU, he was given the highest university faculty rank of Distinguished University Professor of Electrical Engineering.

In 2008, Professor Baliga was a key member of an NCSU team - partnered with four other universities - that was successful in being granted an Engineering Research Center from the National Science Foundation for the development of micro-grids that allow integration of renewable energy sources. Within this program, he is responsible for the fundamental sciences platform and the development of power devices from wide-band-gap semiconductors for utility applications.

Professor Baliga has received numerous awards in recognition for his contributions to semiconductor devices. These include two IR 100 awards (1983, 1984), the Dushman and Coolidge Awards at GE (1983), and being selected among the 100 Brightest Young Scientists in America by Science Digest Magazine (1984). He was elected Fellow of the IEEE in 1983 at the age of 35 for his contributions to power semiconductor devices. In 1984, he was given the Applied Sciences Award by the world famous sitar maestro Ravi Shankar.
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at the Third Convention of Asians in North America. He received the 1991 IEEE William E. Newell Award, the highest honor given by the Power Electronics Society, followed by the 1993 IEEE Morris E. Liebman Award for his contributions to the emerging Smart Power Technology. In 1992, he was the first recipient of the BSS Society's Pride of India Award. At the age of 45, he was elected as Foreign Affiliate to the prestigious National Academy of Engineering, and was one of only 4 citizens of India to have the honor at that time (converted to regular Member in 2000 after taking U.S. Citizenship). In 1998, the University of North Carolina system selected him for the O. Max Gardner Award, which recognizes the faculty member among the 16 constituent universities who has made the greatest contribution to the welfare of the human race. In December 1998, he received the J.J. Ebers Award, the highest recognition given by the IEEE Electron Devices Society for his technical contributions to the Solid-State area. In June 1999, he was honored at the Whitehall Palace in London with the IEEE Lamme Medal, one of the highest forms of recognition given by the IEEE Board of Governors, for his contributions to development of an apparatus/technology of benefit to society. In April 2000, he was honored by his Alma Mater as a Distinguished Alumnus. In November 2000, he received the R.J. Reynolds Tobacco Company Award for Excellence in Teaching, Research, and Extension for his contributions to the College of Engineering at North Carolina State University. In 2011, Dr. Baliga was selected to receive the Alexander Quarles Holladay Medal for Excellence, which recognizes members of the NCSU faculty who over their careers have made outstanding contributions to the University through their research, teaching, and extension services.

In 1999, Prof. Baliga founded a company, Giant Semiconductor Corporation, with seed investment from Centennial Venture Partners, to acquire an exclusive license for his patented technology from North Carolina State University with the goal of bringing his NCSU inventions to the marketplace. A company, Micro-Ohm Corporation, subsequently formed by him in 1999, has been successful in licensing the GD-TMBS power rectifier technology to several major semiconductor companies for world-wide distribution. These devices have application in power supplies, battery chargers, and automotive electronics. In June 2000, Prof. Baliga founded another company, Silicon Wireless Corporation, to commercialize a novel super-linear silicon RF transistor that he invented for application in cellular base-stations and grew it to 41 employees. This company (renamed Silicon Semiconductor Corporation) is located at Research Triangle Park, N.C. It received an investment of $10 Million from Fairchild Semiconductor Corporation in December 2000 to co-develop and market this technology. Based upon his additional inventions, this company has also produced a new generation of Power MOSFETs for delivering power to microprocessors in notebooks and servers. This technology was licensed by his company to Linear Technologies Corporation with transfer of the know-how and manufacturing process. Voltage Regulator Modules (VRMs) using his transistors are currently available in the market for powering microprocessor and graphics chips in laptops and servers.

In 2010, Dr. Baliga was inducted into the Engineering Design Magazine’s “Engineering Hall of Fame” for his invention, development, and commercialization of the Insulated Gate Bipolar Transistor (IGBT), joining well known luminaries (e.g. Edison, Tesla, and Marconi) in the electrical engineering field. The award announcement states: “While working at General Electric in the late 1970s, Baliga conceived the idea of a functional integration of MOS technology and bipolar physics that directly led to the IGBT’s development... it remains undeniable that Baliga’s vision and leadership played a critical role in moving the IGBT from a paper-based concept to a viable product with many practical applications.”