Recent Advances in Power Electronics

Bimal K. Bose, *Fellow, IEEE*

***Abstract*—Power electronics has been defined as a multidisciplinary technology that encompasses power semiconductor devices, converter circuits, electrical machines, signal electronics, control theory, microcomputers, very-large-scale integration (VLSI) circuits, and computer-aided design techniques. Although power electronics engineers polarized in a narrow segment of the spectrum claim to be power electronics specialists, a true specialist in this area should have more or less experience in all the aforementioned component disciplines. This is indeed a challenge as most of these disciplines are going through fast technological evolution. This paper reviews the advancement in some of these key areas, such as power semiconductor devices, converter circuits, and control of power electronics. The technology trends in these areas have also been highlighted.**

I. INTRODUCTION

ELECTRICAL power is processed by power electronics to make it suitable for various applications, such as dc and ac regulated power supplies, electrochemical processes, heating and lighting control, electrical machine drives, induction heating, electronic welding, active power line filtering, static var compensation, etc. The processing involves conversion (dc–ac, ac–dc, dc–dc, and ac–ac) and control using power semiconductor switches. Compared to linear mode power amplification using power semiconductor devices, the switching mode power processing gives higher efficiency with the penalty of harmonic ripples in the load and source sides. In a modern power electronic equipment, there are essentially two types of semiconductor elements: the power semiconductors that can be considered as muscle of the equipment, and the microelectronic control chips that provide the power of the brain. Both elements are digital in nature, except that one manipulates power up to gigawatts and the other handles only milliwatts. The close coordination of these end-of-the-spectrum electronics is offering large size and cost advantages and high level of performance in today's power electronic apparatus.

By using power electronics, we can achieve a high level of productivity in industry and product quality enhancement that cannot be possible by using nonpower electronic methods. Today, power electronics is an indispensable tool in any advanced country's industrial economy. An important aspect of power electronics applications is energy conservation, i.e., more efficient use of electricity. For example, in a variable speed heat pump, energy up to 30% can be saved by providing load-proportional speed modulation of the compressor drive. The additional cost of power electronics can be recovered by energy saving in a reasonably short time, especially where the cost of electricity is high. The use of electric cars, electric trams, and electric subway trains can substantially reduce urban pollution problems. Power electronics permits generation of electrical power from environmentally clean photovoltaic, fuel cell, and wind energy sources. Now we are concerned about acid rain and world greenhouse (global warming due to accumulation of carbon dioxide and other gases) effects. Widespread application of power electronics, especially with an eye for energy conservation and generation of power from environmentally clean sources, can help in solving these problems.

The modern era of power electronics began with the advent of power semiconductor devices. The pnpn triggering transistor, which was later defined as a thyristor or silicon-controlled rectifier (SCR), was invented by Bell Telephone Laboratory in 1956 and was later commercialized by the General Electric Co. Of course, power diodes using silicon or germanium were available prior to that time. Since then, power electronics has gone through a dynamic evolution in the last three decades. The principal research and development efforts in this technology have taken the following directions: power semiconductor devices, converter topologies, analysis and simulation, control and estimation techniques, and control hardware and software.

In this paper, we briefly review the recent advances in power electronics that include power semiconductor devices, converter circuits, and control techniques. The research and development trends in these areas are highlighted.

II. POWER SEMICONDUCTOR DEVICES

Power semiconductor devices are going through a dynamic evolution in recent years. In the history of power electronics, we have never before seen the emergence of so many exotic power semiconductor devices in such a brief span of time. These devices constitute the heart of modern power electronics. It is indeed the most complex, delicate, and "fragile" element in a converter. A power electronics engineer needs to understand the device thoroughly for efficient, reliable, and cost-effective design of a converter. One important trend in power electronics is that the cost of silicon-based power and control devices is

---

Manuscript received October 1, 1990; revised April 4, 1991. A modified version of the paper was presented at the 1990 IEEE Industrial Electronics Conference (IECON'90), Asilomar Conference Center, Pacific Grove, CA, Nov. 27-30, 1990.

The author is with the Department of Electrical Engineering, University of Tennessee, Knoxville, TN 37996.

IEEE Log Number 9104747.

continuously falling, accompanied by the improvement of performance, whereas the same for passive bulky power elements are essentially constant. Power electronics engineers are therefore searching for "silicon solution" of passive power circuit components. An example is the use of resonant and quasi-resonant link principles in the modern switching mode power supplies.

As mentioned before, the age of modern power electronics started by the invention of the thyristor. Since then, we have seen the gradual emergence of other power semiconductor devices, such as triac, gate turn-off thyristor (GTO), bipolar power transistor (BJT), power MOSFET, insulated gate bipolar transistor (IGBT), static induction transistor (SIT), static induction thyristor (SITH), and MOS-controlled thyristor (MCT). The latter four devices, which appeared in the 1980's, can be defined as modern, and these are reviewed in this section.

The evolution of power electronics has generally followed the evolution of power semiconductor devices. Again, power semiconductor device technology has followed the evolution of microelectronics. The researchers in solid-state electronics have worked relentlessly for a long time to improve semiconductor processing, device fabrication, and packaging techniques, and, as a result, today's high-density high-performance high-reliability and high-yield microelectronics chips are being available at such an economical price. Piece by piece, all these technologies have been extremely useful for the evolution of power semiconductor devices. Without these spinoff benefits from solid-state research focused for today's very-large-scale integration (VLSI) electronics, power semiconductor devices could have stayed in the primitive stage.

A thyristor is basically a three-junction pnpn device where pnp- and npn-component transistors are connected in regenerative feedback mode. The device is triggered into conduction by a short gate current pulse, but once the device is conducting, the gate loses control to turn off the device. The modern light-triggered phase control thyristors are available with ratings up to 6000 V, 3500 A. A triac is the integration of a pair of thyristors connected in inverse parallel on the same chip. The three-terminal device can be triggered into conduction in both positive and negative half cycles of supply voltage by applying positive and negative gate trigger pulses, respectively. The state-of-the-art triac has ratings up to 800 V, 40 A. A GTO is basically a thyristor-type device that can be turned on by a positive gate current but can also be turned off by a negative gate current pulse. The turnoff current gain is poor (typically 4 or 5). Because of high switching loss, a GTO converter operates typically within a 1-kHz switching frequency. Modern GTO's are available with ratings up to 4500 V, 3000 A. A BJT is a current-controlled bipolar two-junction device. Its switching speed is considerably faster than that of thyristor-type devices, but it has a characteristic second breakdown problem. The device module power rating can be as high as 1200 V, 800 A. A power MOSFET is a unipolar, majority carrier, "zero-junction," voltage-controlled device. The power MOSFET is the fastest of all devices and can operate in hundreds of kilohertz switching frequency. The device is commonly used in high-frequency switching mode power supplies but is not used in high-power (above a few kilowatts) converters because of large conduction losses. The state-of-the-art devices are available with 600 V, 50 A ratings.

A. Modern Power Devices

IGBT: An IGBT is basically a hybrid MOS-gated turn on/off bipolar transistor that combines the attributes of MOSFET, BJT, and thyristor. Fig. 1 shows the basic structure of IGBT, also indicating its equivalent circuit. The device was commercially introduced in 1983. Its architecture is similar to that of MOSFET except the n^+ layer at the drain has been substituted by a p^+ layer at the collector. The device has high-input impedance of a MOSFET but BJT-like conduction characteristics. If the gate is positive with respect to the emitter, an n-channel is induced in the p region. This forward biases the base-emitter junction of the pnp transistor turning it on and causing conductivity modulation of the n-region, which gives significant improvement of conduction drop over that of a MOSFET. The thyristorlike latching action is prevented by proper impurity concentration of p^+ layer that constitutes the base of the parasitic npn transistor. The device is turned off by zero gate voltage that removes the conducting channel in the p region. The "tail current" in a modern IGBT has been significantly reduced by a neutron-irradiated minority carrier life time control and by adding the extra n^+ buffer layer at the emitter. The device has a higher current density compared to BJT and MOSFET and needs 30% die size of a MOSFET. Its input capacitance (Ciss) is significantly less than that of a MOSFET. Also, the ratio of gate-collector capacitance to gate-emitter capacitance is lower, giving improved Miller feedback effect during high dv/dt turn-on and turn-off. The FBSOA and RBSOA of an IGBT are thermally limited by T_j, and the device does not show any second breakdown phenomena. An IGBT is a faster device than the BJT and can operate in medium power up to 20-kHz switching frequency. The modern IGBT is available with a 1200-V 400-A power rating. The device is finding popularity and is expected to replace BJT's in majority of applications in near future.

SIT: An SIT is a high-power high-frequency device and is essentially the solid-state version of triode vacuum tube. SIT was commercially introduced by Tokin Corp. in 1987. Fig. 2 shows its basic structure. It is a short n-channel vertical device where the gate electrodes are buried within the drain and source n-type epi layers. The device is normally on type but if V is negative, the depletion layer of the reverse-biased p^+n junction will inhibit the drain current flow. It is almost identical to JFET except vertical and buried-gate construction gives lower channel resistance causing lower drop. Besides, lower gate-source

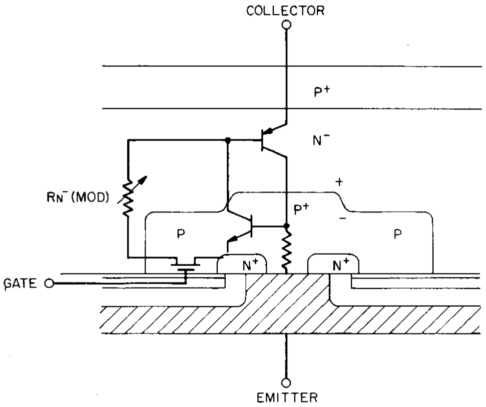


Fig. 1. Basic structure of IGBT.

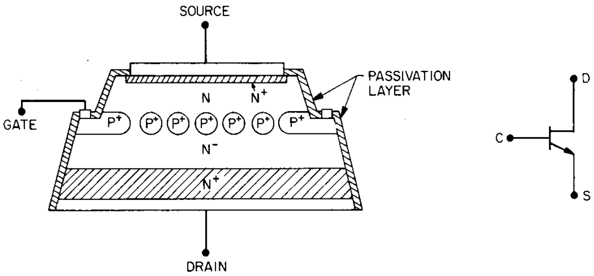


Fig. 2. Basic structure of SIT.

channel resistance gives a lower gate-to-source negative feedback effect. The device has been used in linear mode in audio, VHF/UHF, and microwave amplifiers. The reliability, noise, and radiation hardness of SIT are claimed to be superior to MOSFET. Although the conduction drop is lower than that of equivalent series-parallel combination of MOSFET's, the excessively large drop makes it unsuitable for general power electronics applications unless justified by the need of FET-like switching frequency. In fact, a faster-than-MOSFET switching speed is possible because of lower equivalent gate–source capacitance and resistance. Because it is a majority carrier device, the SOA's are limited by junction temperature. Device paralleling is easy because of positive temperature coefficient characteristics of channel resistance.

Japanese universities and industries have used SIT's in AM/FM transmitters, induction heating, high-voltage low-current power supplies, ultrasonic generators, and linear power amplifiers. Fig. 3 shows a 12-kW 100-kHz resonant converter [25] for induction heating and melting applications.

SITH: An SITH or SI thyristor is a self-controlled GTO-like on–off device that was commercially introduced by Toyo Electric Co. in 1988. Fig. 4 shows the basic structure of SITH and the device symbol. It is essentially a p^+nn^+ diode with a buried p^+ gridlike gate structure. The structure is analogous to SIT except that a p^+ layer has been added to the anode side. Similar to SIT, SITH is a normally on device with the n-region saturated with minority carrier. If the gate is reverse biased with respect to the cathode, a depletion layer will block the anode current flow. The device does not have reverse blocking capability due to the emitter shorting that is needed for high-speed operation. The turn-off behavior of SITH is similar to that of GTO, i.e., the negative gate current is large and the anode circuit shows a tail current. The general comparison with GTO can be summarized as follows:

1) Unlike GTO, SITH is a normally on device.
2) The conduction drop is higher.
3) The turn-off current gain is lower, typically 1 to 3 instead of 4 to 5 for GTO.
4) Both devices show a long tail current.
5) The switching frequency is higher.
6) The dv/dt and di/dt ratings are higher.
7) The SOA is improved.

MCT: An MCT is a thyristorlike trigger-into-conduction device that can be turned on or off by a short pulse on the MOS gate. It is more of a GTO-like device except that the turn-off current gain is very high. In switching speed, it is comparable to IGBT but has less conduction drop. The device was announced by General Electric Co. in November 1988 when samples (500 V/50 A and 1000 V/100 A) were distributed. Recently [8], Harris Semiconductor released developmental MCT's with the ratings of 900 V/15 A, 1000 V/30 A, and 600 V/60 A. The typical parameters of the 600-V/60-A device are $T_j = -55°\text{C}$ to 150°C, conduction drop $(V_d) = 1.1$ V, reapplied $dv/dt = 5000\ \text{V}/\mu\text{s}$, turn-on $di/dt = 1000\ \text{A}/\mu\text{s}$, turn-on time $(t_{\text{on}}) = 1.0\ \mu\text{s}$, and turn-off time $(t_{\text{off}}) = 2.1\ \mu\text{s}$. At present, the device is not available commercially.[1]

An MCT is basically a parallel connection of thousands of identical microcells on the same chip. For example, a 500-V 50-A device contains 100,000 cells in parallel. The basic structure of a cell is shown in Fig. 5, and Fig. 6 gives its equivalent circuit. It is turned on by a negative voltage pulse at the gate and is turned off by a positive voltage pulse. The device has thyristor-like p–n–p–n layers, and pnp–npn regenerative effect turns on the device. If the gate voltage is negative with respect to anode, the p-FET turns on and causes forward biasing of the npn transistor, and this in turn causes triggering of the device. If the gate is positive, the n-FET turns on and short circuits the emitter-base junction of the pnp transistor. This breaks the regenerative feedback loop and the device turns off. The turn-off occurs purely by recombination of minority carriers in the n and p layers. The tailing effect is carefully controlled by proton irradiation so that the conduction drop remains small.

MCT has asymmetric voltage blocking capability and its SOA is claimed to be junction temperature limited.

---

[1] At the time of this writing, it is known that Harris is expected to commercially release 600 V/1200 V, 30 A (rms) and 600 V/1200 V, 60 A (rms) devices in the near future.

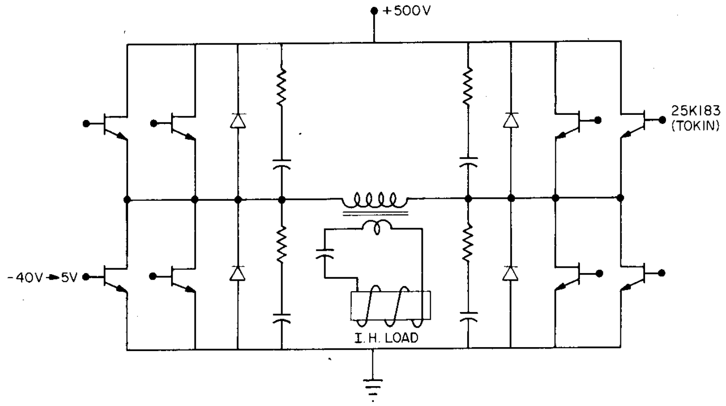


Fig. 3. An SIT resonant inverter for induction heating.

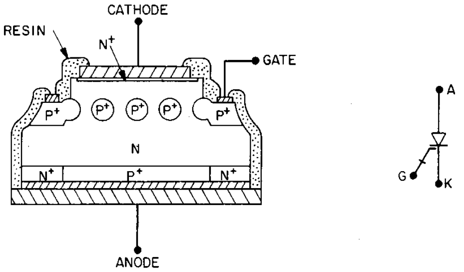


Fig. 4. Basic structure of SITH.

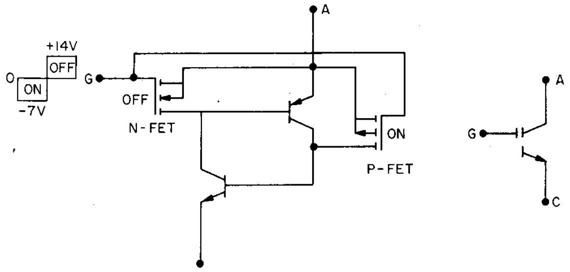


Fig. 6. MCT equivalent circuit and circuit symbol.

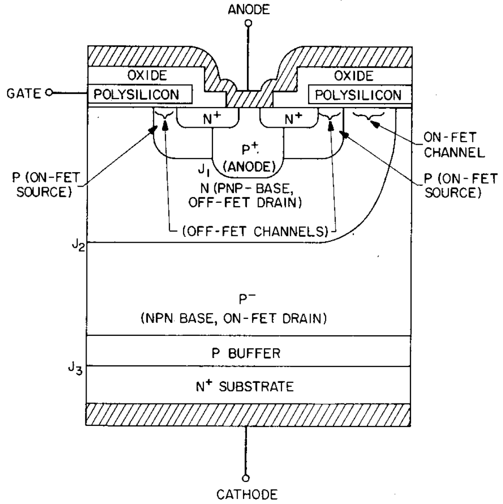


Fig. 5. Basic structure of MCT.

Unlike MOSFET, its input capacitance is fixed because of the absence of Miller effect. With the n-FET normally on, the device is extremely insensitive to dv/dt and T_j triggering. Although the developmental MCT is rated in the T_j range of $-55°C$ to $150°C$, it has been successfully operated at a larger temperature range. At high temperature, the leakage current may be excessive, which will reduce the turn-off current capability (due to higher channel resistance of the off-FET). The MCT's can easily be connected in series–parallel combination for a higher power requirement. In the next generation of power electronics, MCT's are expected to offer a serious challenge to other high-power devices.

The power semiconductor devices of today exclusively use silicon as the basic material. Silicon has been a monopoly over a long time, and possibly this will remain so in the near future. However, the new type of materials, such as gallium arsenide, silicon carbide, and diamond, show tremendous promise for future generation of devices. Silicon carbide and diamond have a large band gap, high carrier mobility, and high electrical and thermal conductivities. As a result, high-power MOSFET-like devices can be built that have a high-power capability, high-frequency low-conduction drop, good radiation hardness, and high junction temperature. The diamond (in synthetic thin film form) looks most promising among all of them. For example, a diamond-power MOSFET can have sixth-order magnitude of power, 50 times higher frequency, less by an order magnitude conduction drop, and 600°C $T_{j\max}$ capability compared to silicon devices [4]. In addition, superconductive power control devices based on Josephson effect also show future promise.

III. Power Converters

A power converter incorporates a matrix of power-switching devices and helps to convert and control the electrical power under the guidance of control electronics. The general classification of converters on functional basis are ac–dc converter (rectifier), dc–dc converter (chopper), dc–ac converter (inverter) and ac–ac converter at same (ac controller) or different frequency (cycloconverter). Often, a practical power electronic system may combine more than one conversion process. The recent advancement of power semiconductor devices and control electronics is creating a tremendous impact on power converter technology in terms of size, cost, reliability, and performance. A general review is given as follows.

A. AC–DC Converter

Traditionally, power electronic converters have used thyristors with phase control and ac line commutation from the beginning to convert ac to dc power for applications, such as dc drives and electrochemical processes. This class of converters is by far the largest in industrial applications. Majority of converter topologies today were inherited from the old gas-tube era. The phase-control thyristors have symmetric voltage-blocking capability and have somewhat slow response characteristics. However, the control of this class of converters is very simple and efficiency is high. The modern high-voltage dc (HVDC) converters used in utility dc transmission systems possibly have the largest power rating in this class of converters. A large number of light-triggered thyristors (up to 6 kV, 5000 A rating) in series–parallel combination constitutes an individual valve of the converter.

The problems with a phase-controlled converter are that it generates lower order harmonics and constitutes lagging displacement factor load on the ac line. Recently, the proliferation of this type of nonlinear load is creating a power-quality problem for utility customers. Traditionally, bulky passive filters have been used to clean harmonics from an ac line. The switched capacitor or thyristor-controlled reactor (TCR) in parallel with a capacitor has been generally used for lagging var compensation. Very recently, PWM-type converters have been proposed for harmonic filtering and var compensation problems. Fig. 7 shows the circuit of an active power line conditioner (APLC) using SITH [42] that functions both as a harmonic filter and var compensator. Basically, an APLC is a high-frequency PWM converter that is controlled to absorb harmonics and vars generated by the phase-controlled converter load as shown. In fact, if the capacitor is paralleled with a battery, it can supply the load power (UPS function) in case of an ac line power interruption. A dual-type APLC using the current-fed principle is introduced later. APLC's are presently expensive, and therefore are not frequently used.

The APLC's are primarily well suited for retrofit applications. It is more economical to integrate the filtering and var compensation functions in a newly installed converter system. Fig. 8 shows a three-phase ac drive with a PWM boost chopper in the dc link. It programs the line current to be sinusoidal and in phase with the voltage wave as shown. In addition, the chopper helps to regulate the capacitor voltage for line voltage fluctuation. Fig. 9 shows the three-phase version [27] of Fig. 8. Note that the dc-link inductance has been transferred to individual phases on the ac side. When the chopper is on, it causes a symmetrical three-phase short circuit on the ac line, and therefore causes large current ripple on the ac side. However, a small capacitor filter will make the line current sinusoidal as shown. A three-phase PWM rectifier controlling the speed of a dc machine is shown in Fig. 10. The current-fed rectifier with reverse-blocking GTO's controls the dc current as well as fabricates the sinusoidal ac line current at a unity power factor. The capacitors on the ac side suppress Ldi/dt transient on GTO's and filter the PWM harmonics.

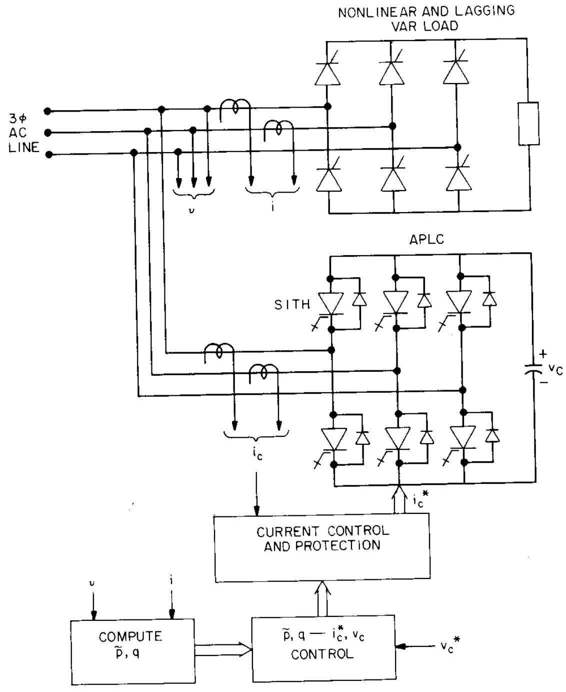


Fig. 7. An active power line conditioner using SITH.

B. AC–AC Converter

Thyristor or triac-based ac voltage controller (same output frequency) using the phase control principle is popularly used in light-dimming control, heating control, and single-phase appliance-type drives. Phase-controlled cycloconverters are used in VSCF (variable speed constant frequency) aircraft-generating systems and large-capacity ac drives. The inherent harmonics and lagging var problems due to phase control are also present here. APLC's, as described before, are active tools to combat these problems. The cycloconverters can be operated in circulating current mode with programmable magnitude of current [43] so that the input-lagging var remains fixed regardless of load variation. Under this condition, a fixed-capacitor bank will restore the input power factor to be

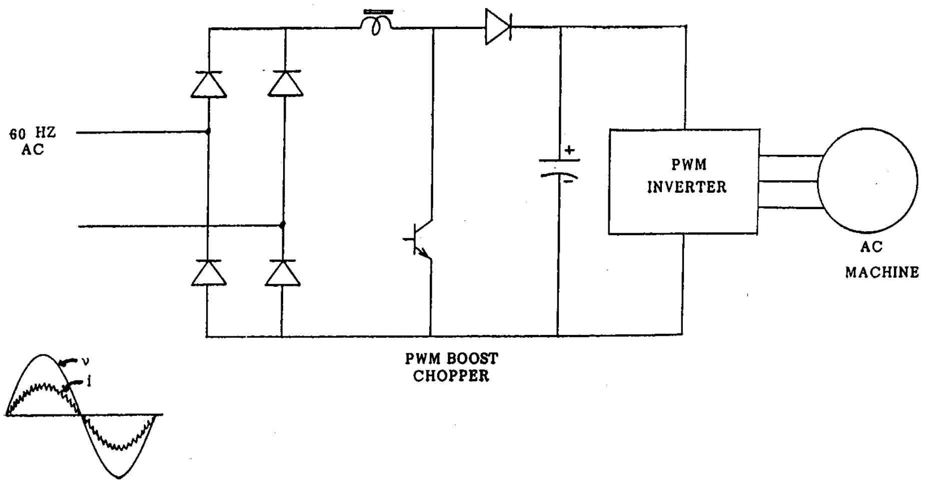


Fig. 8. Single-phase rectifier chopper for an inverter drive.

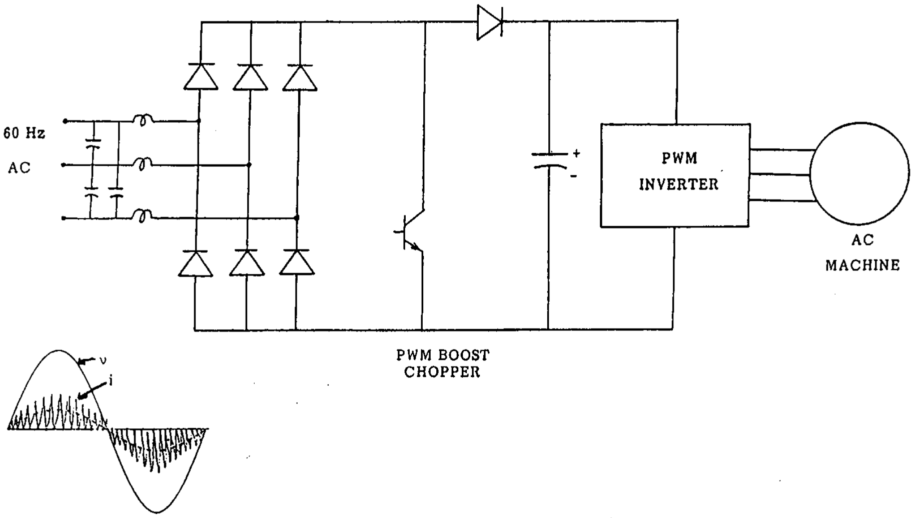


Fig. 9. Three-phase rectifier chopper for an inverter drive.

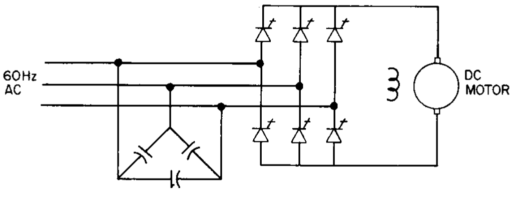


Fig. 10. Three-phase PWM rectifier for a dc drive.

near unity. However, the filter capacitor with the line inductance may cause a harmful resonance problem. Recently, an active filter has been suggested in such installations to absorb the harmful harmonics.

Another class of frequency changer using the PWM principle (known as matrix or Venturini converter) is shown in Fig. 11. The circuit uses a matrix of nine ac switches (inverse-parallel connection of reverse-blocking self-controlled switches) and directly converts the power in a large-frequency range (including dc operation). One advantage of this circuit is that the input power factor can be programmed to be near unity at all operating conditions. However, the difficulty is that high-frequency PWM switches are usually available in an asymmetrical blocking mode.

C. DC–DC Converters

DC–DC converters convert unregulated dc voltage to a regulated or programmable dc voltage at a different level and are commonly used in dc motor drives and switching-mode power supplies (SMPS). The conventional PWM-type converter (also known as a chopper) can be classified as buck, boost, or buck–boost type. A single-quadrant

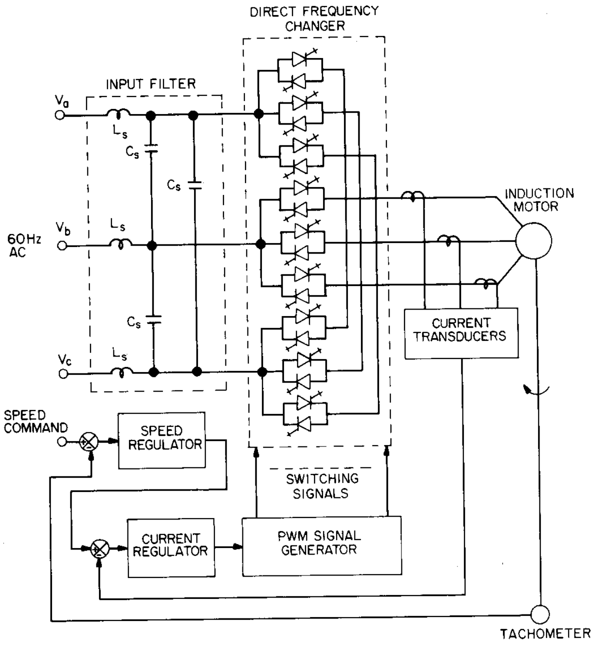


Fig. 11. Three-phase PWM direct-frequency changer.

drive uses a buck converter, a two-quadrant drive uses buck and boost types in combination, and a four-quadrant drive uses an H bridge that provides buck and boost functions for either direction of rotation. High-power converters normally use BJT, IGBT, or GTO switches with switching frequencies up to several kilohertz, whereas low-power low-voltage converters use power MOSFET's at much higher frequencies. The low-power SMPS is usually nonregenerative in nature and uses power MOSFET's in a one-quadrant configuration with a frequency up to 100 kHz. The motivation for high frequency is size reduction of passive components, such as an isolation transformer, a filter inductor, and a capacitor.

The designers of power supplies that are used in computer, telecommunication, and instrumentation applications are under tremendous pressure to reduce the size of dc–dc converters, and the bulk of present R&D efforts are focused in that direction. The complaint is that in this microelectronics era, the size of control and information-processing electronics is shrinking tremendously, but the power supply unit is still bulky, making it incompatible with microelectronic chips. With PWM technique, the switching loss and device stress are high. Any attempt to reduce the size by increasing the switching frequency will adversely affect losses (demanding more heatsink size) and reliability. The class of resonant and quasi-resonant converters practically eliminate the switching-loss and device-stress problems, and therefore switching frequency can be increased up to several megahertz to design a very compact power supply. Squeeze in size permits decentralization of power supply units on electronics circuits boards. In a resonant link converter the dc power is first inverted to a high-frequency ac by a resonant circuit inverter and is then rectified to dc and passed through a low-pass filter. Inverter devices are switched at zero voltage or zero current eliminating the switching loss. However, the conduction loss may be increased somewhat due to a peaky current wave. Although switching loss is eliminated in a resonant converter at a high-resonance frequency, the magnetic and capacitor losses increase, thus adversely affecting the size due to larger heatsink. The quasi-resonant converters can be viewed as a hybrid of PWM and resonant converters. The circuit topology resembles those of PWM converters, but the *LC* tank circuit generates quasi-sine waves that permit zero–voltage or zero–current switching. At several megahertz switching frequency, the tank elements are so small that often the parasitic elements (leakage inductance of transformer and intrinsic capacitance of semiconductor switch) can be gainfully utilized.

D. DC–AC Converters

Inverters can be generally classified as voltage-fed and current-fed types and are mainly used in ac motor drives, UPS systems, APLC systems, and induction heating. The voltage-fed type is by far the most popular for industrial applications. A PWM voltage-fed inverter system for a drive generally uses a diode rectifier in the front end and therefore this system does not have regenerative feedback capability. The PWM control of the inverter regulates the voltage magnitude and harmonic ripple at the output. Both sinusoidal voltage PWM and hysteresis-band current-control PWM methods are widely used. Fig. 12 shows a dual-PWM voltage-fed converter system for an induction motor drive. The PWM rectifier functions in the same manner as the PWM inverter and permits a bidirectional power flow. The system permits regeneration of the drive when the rectifier and inverter functions are interchanged as shown. The additional advantage of the system is that the line side current can be programmed to be sinusoidal at unity power factor. For UPS function, the inverter generates regulated voltage at constant frequency and a battery is coupled to the dc link. If the power demand at the output is purely reactive, the input rectifier can be removed. Such a system, when connected to a utility line, can be controlled to function as an active filter and leading or lagging var generator (APLC). Fig. 13 shows a dual PWM current-fed converter drive system that has a duality configuration with Fig. 11. The capacitor bank permits self-commutation of the devices and operates as a low-pass filter for PWM current waves. Again, the line-side power factor can be controlled to be unity and machine current becomes harmonic free, improving its efficiency and eliminating the acoustic noise problem. Large-power (several thousand HP) GTO inverters of this type with the line-side PWM converter replaced by a phase-controlled converter are popularly used in retrofit induction motor drive applications. Again, as explained before, the PWM inverter in Fig. 13 can be used as an APLC on utility system with the dc input shorted.

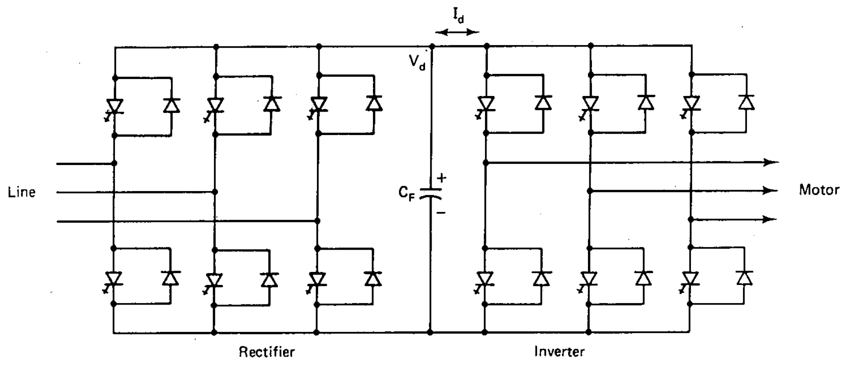


Fig. 12. Dual PWM voltage-fed converter system for an induction motor drive.

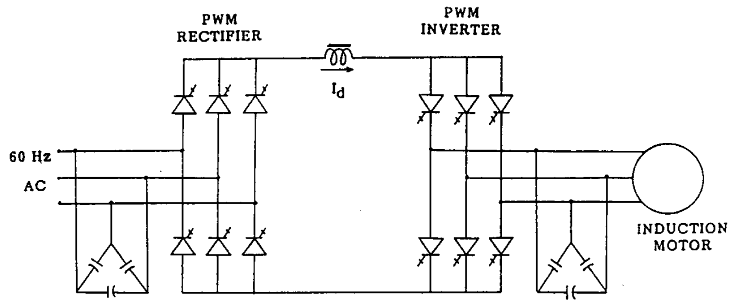


Fig. 13. Dual PWM current-fed converter system for an induction motor drive.

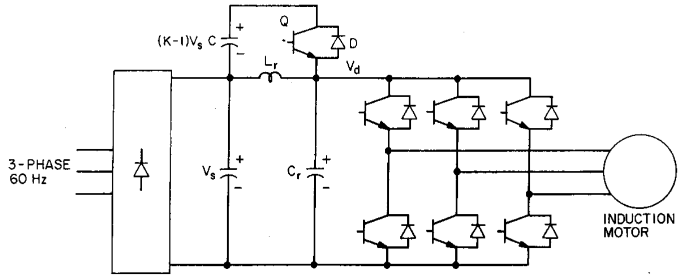


Fig. 14. Resonant dc link inverter system with active voltage clamping.

The resonant link converter techniques that have been popular for switching-mode power supplies are now being extended to variable-voltage variable-frequency power supply at a higher power level for ac motor drives [21]. The usual features, such as high efficiency and small heat-sink size due to switching loss elimination, snubberless operation, elimination of machine acoustic noise, low EMI problem, and longer life of machine insulation (due to low dv/dt) are of immense benefit in such applications. With these features, high-power converters show the potential for integration. This class of converters is expected to be applied in UPS and APLC systems as well. Fig. 14 shows a resonant dc link PWM inverter for an induction motor drive. The input stiff dc voltage V_s is converted to an oscillating dc voltage V_d (at tens of kilohertz) through a resonant circuit. The oscillating voltage pulses with zero crossings permit zero voltage switching of the inverter switches. The inductor initial current is established at every resonant cycle by closing the inverter switches simultaneously. The active voltage-clamping method used permits the link voltage to be limited typically to $1.3V_s$. Fig. 15 shows another resonant dc-link inverter scheme and Fig. 16 shows its voltage and current waves in different operating modes. The dc-link voltage oscillates (typically at 50 kHz) with zero crossing and permits the inverter switching at zero voltage. The bidirectional current initialization circuit establishes a programmable initial current in the resonant inductor so that the voltage wave has constant peak value $(2V_s)$ with the desirable zero crossing interval irrespective of load current.

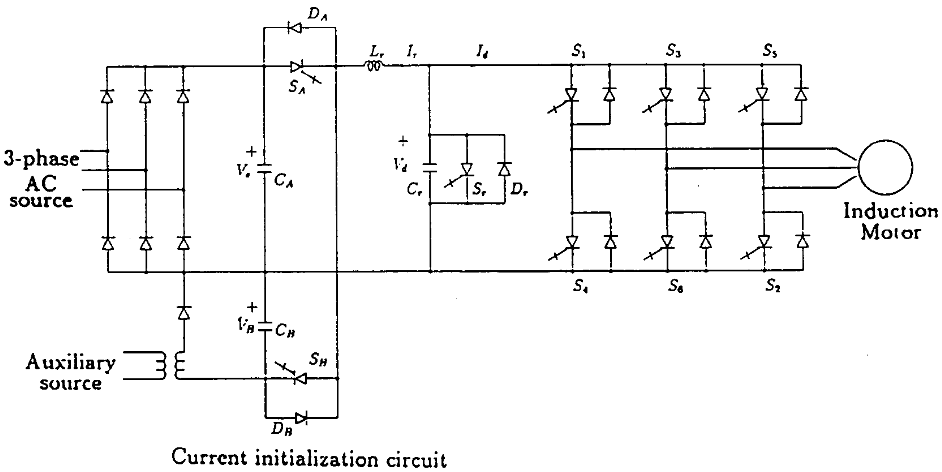


Fig. 15. Resonant dc-link PWM inverter for an induction motor drive.

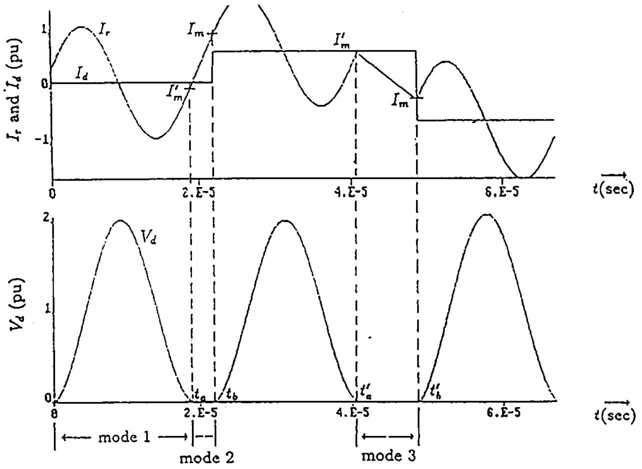


Fig. 16. Resonant-link voltage and current waves.

Although the link voltage is somewhat high, the higher permissible resonance frequency gives less harmonic ripple current at the output. An ideal resonant link inverter should be able to establish a resonant notch at the instant of inverter switching demanded by the PWM controller. Such a scheme generates less harmonic ripple current on the machine due to improved PWM resolution. Fig. 17 shows a quasi-resonant dc-link inverter to achieve this goal [25]. The switch S_c locks the capacitor voltage ($2V_s$) until a notch is initiated by the shunt switch S_r. Recently, series resonant dc link power conversion has also been proposed [51]. The dc resonant link schemes can be extented to ac resonant link schemes [16], [17], but such converters are likely to be less popular because of the need for more expensive ac switches.

E. Power-Integrated Circuits

This section remains incomplete without a review of the recent power-integrated circuits (PIC). An excellent paper in this topic was presented in IECON'89 [31]. In a PIC, the control and power electronics are integrated on the same chip. A PIC is loosely defined as "smart power." The motivation for power circuit integration is cost reduction and reliability improvement. The main problems in PIC synthesis are isolation between high- and low-voltage devices and cooling. A PIC is often differentiated from a high-voltage integrated circuit (HVIC) where the voltage is high but current is small. Low-voltage NMOS, CMOS, and bipolar devices can be conveniently integrated with MOS-gated power devices. Recently, a large family of PIC's that include power MOSFET smart switch, half-bridge inverter driver, H-bridge inverter, two-phase step motor driver, one-quadrant chopper for dc motor drive, three-phase brushless dc motor driver, three-phase diode rectifier-PWM inverter are being available. Evidently, the majority of PIC's are being targeted for motion control applications. Recently, application specific PIC's (ASPIC) are also

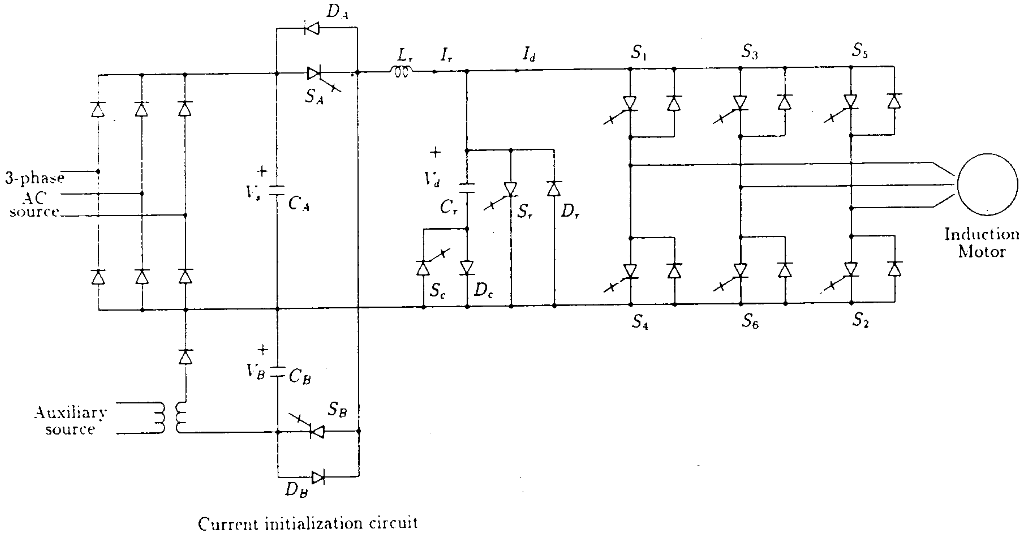


Fig. 17. Quasi-resonant dc-link inverter.

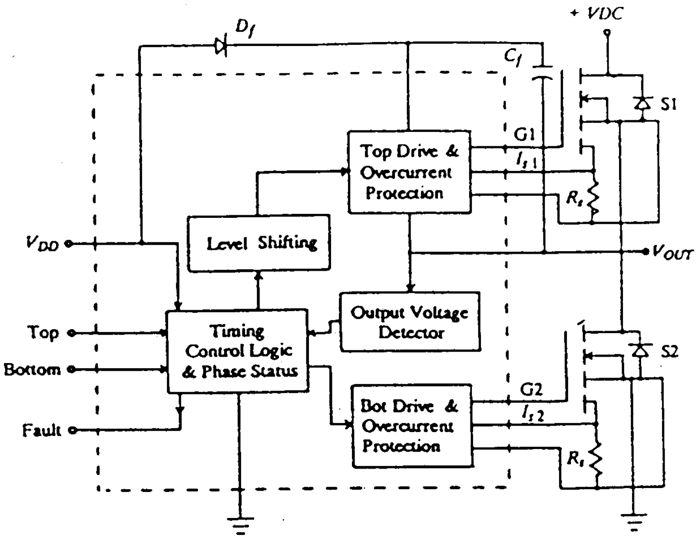


Fig. 18. Half-bridge integrated power MOSFET driver (Harris GS6000/1).

being available in the market. Fig. 18 shows, for example, a half-bridge power MOSFET driver manufactured by Harris (GS6000/1). It is more appropriate to define it as an HVIC. The diode–capacitor charge pump permits the gate drive command of switch S1 to be level shifted. The driver uses 500 V junction isolation and gives logic lockout protection between the power devices. Other protection features include overcurrent (using integrated current sensors, if desired), logic supply undervoltage detection, and output state monitor when V_{out} does not follow the logic command. The detected faults are reported to the central controller, which is then given as a logic output.

A few recent converter trends can be summarized as follows before exiting this section. (1) Force-commutated voltage-fed inverters using thyristors (such as the McMurray inverter, McMurray Bedford inverter, etc.) are already obsolete. This means that inverter-grade thyristors have no future. (2) Low-cost low-power phase-controlled apparatus, such as a triac light dimmer and some types of home appliance controllers will continue to be used for a long time. (3) Phase-controlled-type converters that now dominate on utility systems are expected to be gradually replaced by PWM-type converters, and voltage-fed class appears to be of maximum promise. This will ultimately include the large HVDC-type converters. More stringent power quality standards for utility systems will discourage harmonics and var loading by phase-controlled converters. As the high-frequency high-power devices become cheaper, active power line conditioners will find favor principally in retrofit applications. The new converter systems will be designed with PWM rectifiers in the front end solving the power quality problems. Of course, in the low-power range, the front-end diode rectifier-boost chopper method of power line conditioning will be favored. (4) Phase-controlled cycloconverters are expected to be gradually replaced by dual voltage-fed PWM converters. This includes the presently popular cycloconverter-fed multimegawatt ac drives. The future of phase control thyristors, which has dominated for so long in power electronics, appears to be bleak. (5) Force-commutated current-fed inverters (such as the auto-sequential inverter, four-legged neutral-commutated inverter, etc.) are being rendered practically obsolete. Single- or dual-GTO current-fed PWM converters are their viable replacement. (6) Most BJT converters are expected to disappear, yielding their place to IGBT converters. (7) Power MOSFET's will remain as viable devices in low-voltage low-power high-frequency applications. (8) The MCT's, when fully developed, are expected to heavily challenge the GTO's and IGBT's.

IV. Control of Power Electronics

Control plays a key role in the performance of a power electronic system. Recently, the advent of microelectronic chips has brought tremendous size and cost reduction to the controller accompanied by performance improvement. In general, the control electronics can be classified as discrete hardware, microcomputer software, and VLSI hardware.

The control used in a particular power electronic system depends on the converter topology, the driving load, and the desired system performance. Traditionally, discrete analog and digital hardware elements, such as op amps, logic NAND/NOR gates, decoders, counters, etc., have been used in the control of power electronics. Simple power electronic equipment, such as a triac light dimmer or thyristor battery charger will prefer this type of control. Very-high-frequency power electronics, such as a switching-mode power supply, use dedicated hardware control because of simplicity and fast response.

A. Microcomputer Control

A complex power electronics system, such as an electrical machine drive, HVDC converter and UPS system, will prefer to use microcomputer control. The microcomputer control has several advantages. It provides significant cost reduction in control hardware, improves system reliability, and eliminates drift and electromagnetic interference (EMI) problems. The hardware can be designed in a universal manner, but the software can be flexible, i.e., it can be altered or updated as the system requirement changes. Besides, information storage, monitoring, diagnostics, and hierarchical control capability are additional beneficial features of microcomputer control. The complex computation and decision-making capabilities of modern high-speed microcomputers with large functionality are permitting high-performance real-time controls, such as vector control, sliding-mode control, model-referencing-adaptive (MRAC) control, self-tuning control, expert system control, fuzzy control, and state and parameter estimations for power electronics systems.

Since the introduction of microcomputer by the Intel Corp. in 1971 the technology has gone through intense evolution. Examples of popular Intel microcomputers today are the single-chip 80C51 (8-b) and 80C196 (16-b) microcontrollers. Hitachi H8/532 and Siemens 80515 that belong to the 8051 family are also popular. The age of modern digital signal processors (DSP) started by the introduction of the TMS32010 (16-b) by Texas Instruments. Faster program execution is possible in DSP due to its Harvard architecture that permits overlap of instruction fetch and execution of consecutive instructions. In addition, the chip uses a dedicated hardware multiplier and barrel shifter, which permits these functions in one instruction cycle time. A control-oriented version of the chip (TMS320C14) has 4 kW ROM/EPROM, four 16-b timers, 6-channel PWM D/A, and 16-b I/O and it operates at a 160-ns instruction cycle time. Recently, C20 and C30 families have been introduced. The C25 chip, for example, is fixed-point type like its predecessors and has a 100-ns cycle time. But the C30 DSP is a 32-b floating-point type that executes instructions in 60 ns. Table I summarizes the essential features of C30 chip. The floating-point computation has the advantage that no scaling calculation is required for programming. Texas Instruments is expected to announce soon the C50 type (16-b fixed-point) with a 35-ns cycle time. An interesting architecture of the 32-b machine is RISC (reduced instruction set computer) architecture, which, because of its simplicity and single-cycle per-instruction operation, can considerably enhance the speed of microprocessors. An example of a modern powerful RISC machine is the Intel i860 (64-b floating-point with 150 MOPS at 50 MHz, 6 ns cycle time) that gives supercomputer capability to a personal computer. The RISC processor, because of its simple and fast instruction set, is well suited for PC applications. Although the Inmos ''Transputer''-type RISC has been occasionally used in power electronics systems, RISC can hardly compete with DSP's because of poor functionality of the instructions.

In real-time control applications, the microcomputer interacts with the physical system through AD/DA converters because the system variables are usually analog in nature. The general control functions in a power electronics system include thyristor gate firing control, closed-loop control, digital filtering, nonlinearity compensation, PWM control, sequencing control, monitoring and warning, data acquisition, diagnostics, etc. The advanced microcomputer functions may include performance optimization by on-line search, on-line parameter and state estimation, optimal and adaptive control, fault tolerant control, expert and fuzzy control, etc. In the design of microcomputer control, the software functions are first

TABLE I
KEY FEATURES OF A TMS320C30 DIGITAL SIGNAL PROCESSOR

32-b floating-point DSP
Computation rate—33 MFLOPS (60 ns cycle time)
One-cycle multiplication and barrel shifting
Two 1 K × 32-b on-chip RAM
4 K × 32-b on-chip ROM
Two timers
Parallel and serial I/O
DMA capability
Assembly and C-language—IBM PC or VAX based
1.0-μm CMOS chip—70 000 transistors

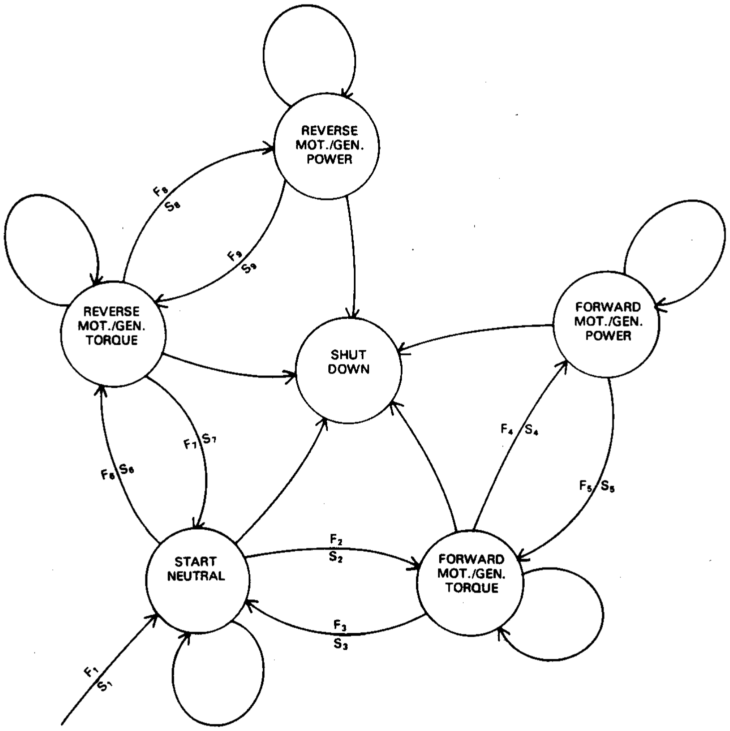


Fig. 19. Sequencing control diagram of an ac drive system.

identified and grouped as different tasks on the basis of sampling intervals. The application routines under different tasks are executed in sequence depending on the priority by the executive software. One important task under microcomputer control is the sequencing function, mentioned earlier. Fig. 19 shows a typical sequencing control diagram of an ac drive system. Each circle represents a mode of operation, and the arrows indicate possible paths of transition. A transition is initiated when a set of conditionals relating software parameters is satisfied. Transitional criteria can be defined by a Boolean function (F_n). If the Boolean function toward the arrow is not satisfied, the control falls back in the same mode repeatedly as shown by a loop arrow. Once function F_n is satisfied, the controller performs a set of action routines (S_n) and smoothly transitions to a different mode.

B. VLSI Control

Typically, a chip containing more than 100 000 devices can be defined as a VLSI chip. It is a functional chip that works alone or in conjunction with other VLSI chips that may include microcomputers. The advantages of VLSI control are low cost for high-volume applications, improvement of speed due to parallel signal processing, higher reliability, and low power consumption. The application specific IC's (ASIC) using semicustom CMOS VLSI are becoming very popular. The dominant member

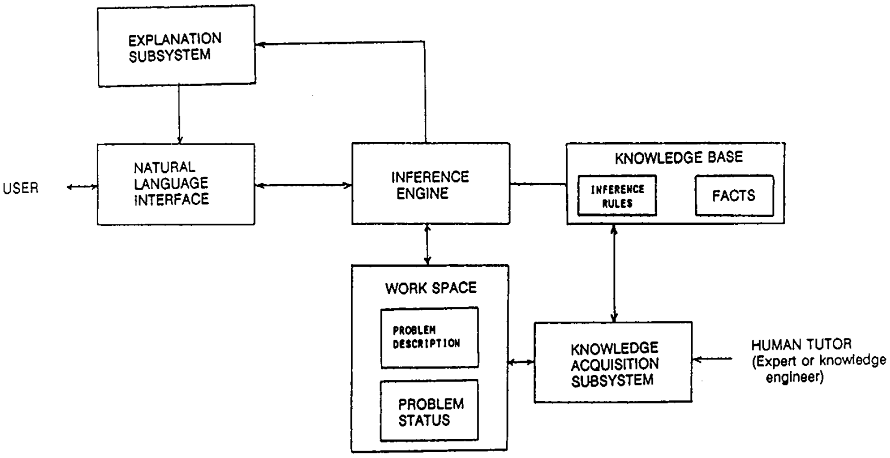


Fig. 20. A simple structure of a knowledge-based expert system.

in this family is the gate-array IC that consists of a matrix of large number of NAND or NOR gates. The gates, along with a few analog devices, are wired to perform a certain dedicated function. A programmable gate-array circuit permits flexible logic system design that can be erased and programmed like an EPROM. The standard-cell ASIC contains functional digital and analog elements, such as a counter, decoder, RAM, ROM, microcontroller, AD/DA converter, op amp, comparator, etc., on the same chip. The total functional circuit is synthesized by calling the appropriate components from the library and interconnecting them. A standard-cell ASIC gives improved performance and consumes less "real estate" on the chip.

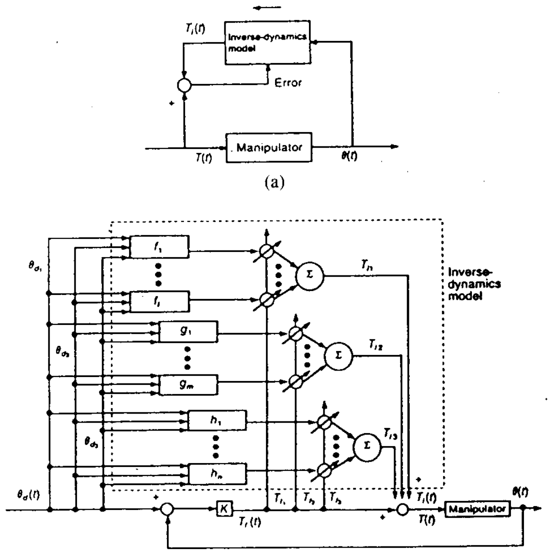
C. Expert and Fuzzy Control

The expert and fuzzy control techniques are gradually making inroads in the control of power electronics. Expert system (ES) is a branch of artificial intelligence that deals with embedding the human expertise in a certain domain in the computer program so that it can replace the human expert. The software structure of an expert system is based on an inference engine and a knowledge base. A simple structure of knowledge-based ES is shown in Fig. 20. The knowledge or rule base consists of a set of production rules in the form of "IF· · ·THEN" statements supported by data or facts. A "knowledge engineer" acquires the knowledge from the human expert and converts it into software. The inference engine is a reasoning mechanism that interrogates the rules and performs an action routine if a certain rule is validated. The problem is actually solved in workspace. Although ES techniques have hardly been applied in power electronics, it has tremendous potentiality in automating system design, modeling, simulation, real-time control, tests, and diagnostics.

Fuzzy logic, unlike the crispy logic in Boolean theory, deals with uncertain or imprecise situations. Fuzzy control is generally based on heuristics that are derived from the general behavior of the process. A variable in fuzzy logic may have sets of values that are characterized by linguistic expressions. For example, the machine speed as a fuzzy variable can be defined as "large negative," "small negative," "small positive," "large positive," etc. But a fuzzy variable in a particular set is characterized by a membership function that varies from 0 to 1. A fuzzy control algorithm consists of an ordered sequence of instructions where the variables may contain fuzzy assignment, fuzzy conditional, and fuzzy action statements. A fuzzy expert system combines the fuzzy and expert control principles. The fuzzy control is better suited to a process where the model is complex or ill defined. It is also suited to a system where the model has high nonlinearity with a parameter-variation problem and feedback sensor signals are imprecise. In fuzzy control, the number of rules are few and the control is adaptive in nature giving superior control features for parameter variation and load disturbance effect. Again, fuzzy control has hardly been applied in power electronics system [45], [46].

D. Neural Networks

Neural networks or neurocomputing technology is recently gathering momentum for process control applications but has hardly penetrated in the power electronics area. The term "neural network" comes from the analogy of the nervous system in the human brain where large numbers of nerve cells are interconnected by input dendrites and output axons. The input parallel signals flowing from other cells are processed, and if the output exceeds a threshold value, it is propagated to other cells in parallel through the axons. A neural-computing network, in general, can be looked on as a parallel-input parallel-output distributed computing system where a set of first-order nonlinear differential equations are solved simultaneously. The neural network algorithm can be implemented on a special-purpose analog computer or a cluster of DSP's, although much of the present developmental work involves simulation study on conventional digital computer. Very recently, a neural network chip is also



(a)

(b)

Fig. 21. Neural network inverse dynamics learning system of a robotic manipulator.

being made available that can be used for control as well as feedback signal processing of a system. With neural networks, the problem of control can be considered to be a pattern recognition problem where the patterns to be recognized are "change" signals that map into "action" signals for specified system performance. A practical neural network may consist of multiple layers with the intermediate layers "hidden." The learning of a neural network consists of varying the weighting coefficients (gains) of the input signals to achieve a certain transfer characteristics, and it can be done either by on-line or off-line method. A simple example of neural network application proposed in a nuclear power plant consists of sampling the monitoring instruments signals and combining them with appropriate weighting coefficients to indicate the general health of the plant. An example of an application in a nonlinear robotic manipulator system is shown in Fig. 21 [13]. The neural network generates the inverse dynamics model of the manipulator and provides adaptive feedforward nonlinearity compensation in the whole region of operation. The learning of the network, i.e., tuning of the model (by varying the weighting coefficients as shown) occurs by what is known as the error-back propagation method. Very recently, an attempt has been made to replace hysteresis-band current control by neural network current control in a PWM inverter [14].

V. CONCLUSION

The paper describes recent advances in several key areas of power electronics technology, such as power semiconductor devices, power converter circuits, and control of power electronics. The structure and characteristics of IGBT, SIT, SITH, and MCT devices have been reviewed. The principal converter types and their recent trends have been described. A brief review of power integrated circuits has also been included. The features of microcomputer and VLSI control have been described and the recent advancement in microcomputers has been highlighted. Finally, the principles of expert system, fuzzy control and neural network have been described.

It appears that future R&D efforts in power electronics will be principally focused in two directions: (1) new and improved devices and (2) microcomputer-based high-performance control using expert system, fuzzy control, and neural networks. The expert system will also provide tremendous capability in automating system design, simulation, tests, and diagnostics. High-temperature superconductive materials, when used successfully, will have tremendous impact on power electronics technology and its applications.

The real revolution in power electronics is yet to come, possibly in the not-too-distant future. This new era will begin with the advent of gallium arsenide, silicon carbide, and diamond power semiconductor devices. The impact will be significantly more than that has been brought by thyristors. However, to attain this goal, we need to invest prolonged and painstaking R&D efforts in processing and fabrication techniques with these new materials. If microelectronics technology also advances at its present pace, then the real capability of power electronics in this new era is awesome to comprehend. Undoubtedly then, power electronics will emerge as a mighty electrical engineering discipline.

REFERENCES

[1] B. K. Bose, *Power Electronics and AC Drives.* Englewood Cliffs, NJ: Prentice-Hall, 1986.
[2] N. Mohan, T. M. Undeland, and P. Robbins, *Power Electronics.* New York: Wiley, 1989.
[3] B. K. Bose, "Evaluation of modern power semiconductor devices and future trend of converters," *IEEE-IAS Annu. Meeting Conf. Rec.*, San Diego, CA, Oct. 1989, pp. 790-797.
[4] K. Shenai, R. S. Scott, and B. J. Baliga, "Optimum semiconductors for high power electronics," *IEEE Trans. Electron Devices*, vol. 36, no. 4, pp. 1811-1823, Sept. 1989.
[5] B. R. Pelly, "Power MOSFETS—A status review," *Int. Power Electron. Conf. Rec.*, Tokyo, pp. 19-32, 1983.
[6] B. J. Baliga, M. Chang, P. Shafer, and M. W. Smith, "The insulated gate transistor (IGT)—A new power switching device," *IEEE-IAS Annu. Meeting Conf. Rec.*, pp. 794-803, 1983.
[7] V. A. K. Temple, "MOS controlled thyristor—A new class of power devices," *IEEE Trans. Electron Devices*, vol. ED-33, no. 10, pp. 1609-1618, 1986.
[8] Harris Semiconductor, Developmental MCT Spec. Sheet for MCTA60P60, Oct. 12, 1990.
[9] B. K. Bose, "Power electronics—An emerging technology," *IEEE Trans. Ind. Electron.*, vol. 36, no. 3, pp. 403-412, Aug. 1989.
[10] ——, "Technology trends in microcomputer control of electrical machines," *IEEE Trans.*, vol. IE-76, pp. 311-324, Apr. 1988.
[11] E. Ohno, "The semiconductor evolution in Japan—a four decade long maturity thriving to an indespensible social standing," *Int. Power Electron. Conf. Rec.*, Tokyo, April 1990, pp. 1-10.
[12] B. K. Bose (ed.), *Adjustable Speed AC Drive Systems.* New York: IEEE Press, 1981.
[13] M. Kawato, Y. Uno, M. Isobe, and R. Suzuki, "Hierarchical neural network model for voluntary movement with application to robotics," *IEEE Control Systems Magazine*, pp. 8-15, Apr. 1988.
[14] F. Harashima, Y. Demizu, S. Kondo, and H. Hashimoto, "Application of neural networks to power converter control," *IEEE IAS Annu. Meeting, Conf. Rec.*, San Diego, CA, Oct. 1989, pp. 1086-1091.

[15] M. Morimoto, K. Oshitani, K. Sumito, and S. Sato, "New single-phase unity power factor PWM converter-inverter system," *IEEE PESC Conf. Rec.*, Milwaukee, WI, 1989, pp. 585-589.

[16] F. C. Schwarz, "A double-sided cycloconverter," *IEEE Trans. Ind. Electron.*, vol. IE-28, no 4, pp. 282-291, Nov. 1981.

[17] S. K. Sul and T. A. Lipo, "Design and performance of a high frequency link induction motor drive operating at unity power factor," *IEEE Trans. Industry Applications*, vol. 26, no. 3, pp. 434-440, May/June 1990.

[18] R. L. Steigerwald, "High frequency resonant dc-dc converters," *IEEE Trans. Ind. Electron.*, vol. IE-31, pp. 181-191, May 1984.

[19] ——, "A comparison of half-bridge resonant converter topologies," *IEEE Trans. Power Electron.*, vol. PE-3, no. 2, pp. 174-182, April, 1988.

[20] F. C. Lee, W. A. Tabisz, and M. M. Jovanovic, "Recent developments in high frequency quasi-resonant and multi-resonant converter technologies," *European Power Electron. Conf. Rec.*, Aachen, Germany, 1989, June, pp. 401-410.

[21] D. M. Divan, "The resonant dc link converter—A new concept in static power conversion," *IEE IAS Annu. Meeting Conf. Rec.*, Sept. 1986, pp. 648-656.

[22] D. M. Divan and G. Skibinski, "Zero switching loss inverters for high power applications," *IEEE IAS Annu. Meeting Conf. Rec.*, Atlanta, GA, Oct. 1987, pp. 627-634.

[23] B. K. Bose (ed.), *Microcomputer Control of Power Electronics and Drives.* New York: IEEE Press, 1987.

[24] J. S. Lai and B. K. Bose, "An induction motor drive using an improved high frequency resonant dc link inverter," *IEEE-PESC Conf. Rec.*, San Antonio, TX, June 1990, pp. 792-799.

[25] ——, "High frequency quasi-resonant dc voltage notching inverter for ac motor drives," *IEEE-IAS Annu. Meeting Conf. Rec.*, Seattle, WA, Oct. 1990, pp. 1202-1207.

[26] M. S. Adler, K. W. Owyang, B. J. Baliga, and R. A. Kokosa, "The evolution of power device technology," *IEEE Trans. Electron Devices*, vol. ED-31, no. 11, pp. 1570-1591, Nov. 1984.

[27] A. R. Prasad, P. D. Ziogas, and S. Manias, "An active power factor correction technique for three-phase diode rectifiers," *IEEE-PESC Conf. Rec.*, Milwaukee, WI, June 1989, pp. 58-66.

[28] M. Hombu, S. Ueda, and A. Ueda, "A current source GTO inverter with sinusoidal inputs and outputs," *IEEE Trans. Industry Applications*, vol. IA-23, no.2, pp. 247-255, Mar./Apr. 1987.

[29] B. K. Bose, "Adjustable speed ac drives—A technology status review," *Proc. IEEE*, vol. 70, no. 2, pp. 116-135, Feb. 1982.

[30] J. G. Kassakian and M. F. Schlecht, "High-frequency high density converters for distributed power supply systems," *Proc. IEEE*, vol. 76, no. 4, pp. 362-376, Apr. 1988.

[31] T. M. Jahns, "Designing intelligent muscle into industrial motion control," *IEEE IECON'89, Conf. Rec.*, Philadelphia, PA, Nov. 1989, pp. 1-13.

[32] M. Venturini and A. Alesina, "The generalised transformer: A new bidirectional sinusoidal waveform frequency converter with continuously adjustable input power factor," *IEEE-PESC Conf. Rec.*, 1980, pp. 242-252.

[33] H. Inaba *et al.*, "A new speed control system for dc motors using GTO converter and its application to elevators," *IEEE Trans. Industry Applications*, vol. IA-21, no. 2, pp. 391-397, Mar./Apr. 1985.

[34] C. L. Neft and C. D. Schauder, "Theory and design of a 30 hp matrix converter," *IEEE-IAS Annu. Meeting Conf. Rec.*, 1988, pp. 934-939.

[35] J. Nishizawa, "Application of the power static induction devices," in *Proc. Int. PCIM*, Tokyo, 1988, pp. 1-12.

[36] V. A. K. Temple, "Power device evolution and MOS-controlled thyristor," in *Proc. Int. PCIM*, 1987, pp. 23-29.

[37] F. C. Lee, (ed.), "High-frequency resonant, quasi-resonant, and multi-resonant converters," Virginia Power Electronics Center, 1989.

[38] B. K. Bose (ed.), *Modern Power Electronics.* New York: IEEE Press, 1992.

[39] L. A. Zadeh, "Making computers think like people," *IEEE Spectrum*, pp. 26-45, Aug. 1984.

[40] M. Nishihara, "Power electronics diversity," *Int. Power Electron. Conf. Rec.*, Tokyo, 1990, pp. 21-28.

[41] H. Ogiwara, O. Kimura, T. Dezaki, M. Nakaoka, and T. Maruhashi, "Development of SIT high frequency resonant inverter for metal melting uses," in *Proc. PCI'87*, 1987, pp. 146-155.

[42] M. Kohata *et al.*, "Compensator for harmonics and reactive power using static induction thyristors," in *Proc. ENE*, 1987, pp. 1265-1270.

[43] Y. Tamura *et al.*, "Control method and upper limit of output frequency in circulating current cycloconverter," in *Proc. Int. Static Power Conv. Conf.*, 1982, pp. 313-323.

[44] W. Pedrycz, *Fuzzy Control and Fuzzy Systems.* New York: Wiley, 1989.

[45] B. da Silva, G. E. April, and G. Olivier, "Real time fuzzy adaptive controller for an asymmetrical four quadrant power converter," *1987 IEEE-IAS Annu. Meeting Conf. Rec.*, 1987, pp. 872-878.

[46] Y. F. Li and C. C. Lau, "Development of fuzzy algorithms for servo systems," *IEEE Control Systems Magazine*, pp. 85-91, April 1989.

[47] Y. Dote and B. K. Bose, "Fuzzy CAD for variable structure PID controller," *IEEE-IECON'89*, pp. 705-708, 1989.

[48] B. Bavarian, "Introduction to neural networks for intelligent control," *IEEE Control Systems Magazine*, pp. 3-7, Apr. 1988.

[49] M. Kawato *et al.*, "Hierarchical neural network model for voluntary movement with application to robotics," *IEEE Control Systems Magazine*, pp. 8-15, Apr. 1988.

[50] Texas Instruments, *Third-Generation TMS320 User's Guide.* Houston, TX: 1988.

[51] Y. Murai *et al.*, "High frequency series resonant DC link power conversion," *IEEE-IAS Annu. Meeting Conf. Rec.*, 1988, pp. 772-779.

Bimal K. Bose (S'59-M'60-SM'78-F'89) received the B.E. degree from Calcutta University, Calcutta, India, the M.S. degree from the University of Wisconsin, Madison, and the Ph.D. degree from Calcutta University in 1956, 1960, and 1966, respectively.

He was a Member of the Faculty at Calcutta University (Bengal Engineering College), where he was awarded the Premchand Roychand Scholarship and the Mouat gold medal for outstanding research contributions. In 1971, he joined Rensselaer Polytechnic Institute, Troy, NY, as a member of the faculty in the Electrical Engineering Department, where he was responsible for organizing the power electronics program for five years. From 1976 to 1987, he was a research engineer in General Electric Research and Development Center, Schenectady, NY. In 1987, he joined the University of Tennessee, Knoxville, as Professor of Electrical Engineering (Condra Chair of Excellence in Power Electronics). He is also the Distinguished Scientist at the EPRI-sponsored Power Electronics Applications Center in Knoxville and Senior Advisor to Beijing Power Electronics Research and Development Center in China. He has served as a consultant in a number of industries, which include General Electric R&D Center, Bendix Corp., Lutron Industries, PCI Ozone Corp., and Research Triangle Institute, and has visited a number of countries as a UN consultant. His research interests are power converters, ac drives, microcomputer control, and application of fuzzy logic and expert system in power electronics. He has published over 90 papers and holds 16 U.S. patents (3 more pending). He is the author of *Power Electronics and AC Drives* (Englewood Cliffs, NJ: Prentice-Hall, 1986), which was translated into Japanese and Chinese. In addition, he edited the IEEE books *Adjustable Speed AC Drive Systems* (1981) (translated into Chinese) and *Microcomputer Control of Power Electronics and Drives* (1987). He also contributed to the *AC Drives in Systems and Control Encyclopedia* (New York: Pergamon, 1987).

Dr. Bose is Chairman of the IEEE Industrial Power Converter Committee, Associate Editor of the IEEE Transactions on Industrial Electronics and is Power Electronics Committee Chairman of the Industrial Electronics Society. He has been a keynote speaker in a number of national and international conferences and has served in the committees of a large number of professional organizations. He is listed in *Who's Who in Technology*, *International Who's Who in Engineering*, *Personalities in America*, *Biography International*, *Directory of World Researchers*, *Leading Consultants in Technology*, and *Who's Who in Electromagnetics*. The Institute of Electronics and Telecommunication Engineers, India, gives the Bimal Bose Award in Power Electronics annually to an Indian engineer for outstanding contributions in power electronics. He is a recipient of the GE publication award and the silver patent medal.