**INTERNATIONAL CONFERENCE ENERGY OF MOLDOVA - 2005**
**September 21-24, 2005 - Chisinau, Rep.Moldova**

# RECENT ADVANCES AND FUTURE TRENDS IN POWER ELECTRONICS AND ELECTRIC DRIVES

**Bimal K. Bose[1], Valentin Oleschuk[2], Alexandr Sizov[2] and Evgeni Yaroshenko[2]**
[1] The University of Tennessee at Knoxville, USA
[2] Power Engineering Institute of the Academy of Sciences of Moldova Moldova

**Abstract** – *The technology of power electronics has gone through rapid technological advancement during the last four decades, and recently, its applications are fast expanding in industrial, commercial, residential, military and utility environments. In the global industrial automation, energy conservation and environmental pollution control trends of the 21st century, the widespread impact of power electronics is inevitable. The paper begins with a discussion on global energy generation scenario and the corresponding environmental pollution problem. The mitigation of this problem is then discussed with particular emphasis on energy saving with the help of power electronics. A brief but comprehensive review of the recent advances of power electronics that includes power semiconductor devices, converters, machines, drives and control is incorporated in the paper. Finally, a prognosis for the 21st century has been outlined.*

**Keywords** – *Converter, drive, energy, power electronics.*

## 1. INTRODUCTION

Power electronics has now firmly established its importance as indispensable tool in industrial process applications after decades of technological evolution. Fortunately, we are now living in an era of industrial renaissance when not only power electronics but also computers, communication, information, and transportation technologies are advancing rapidly. The advancement of these technologies has brought the geographically remote areas in the world closer day by day. We now live in a truly global society, particularly with the advancement of internet communication.

In the new global market, free from trade barriers, the nations around the world will face fierce industrial competitiveness for survival and improvement of living standards. In the highly automated industrial environment struggling for high quality products with low cost, it appears that two technologies will be most dominating: computers and power electronics with motion control. After the great inventions of transistor (in 1948) and thyristor (in 1956) gradually came the modern eras of integrated circuits, computers, communication and robot technologies. It is often said that solid-state electronics brought in the first electronics revolution, whereas solid-state power electronics brought in the second electronics revolution. It is interesting to note that power electronics essentially blends the technologies brought in by the mechanical age, electrical age, and electronics age. It is truly an interdisciplinary technology.

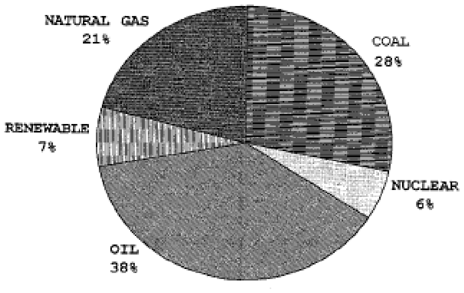
## 2. ENERGY AND ENVIRONMENTAL ISSUES

### 2.1 Energy Scenario

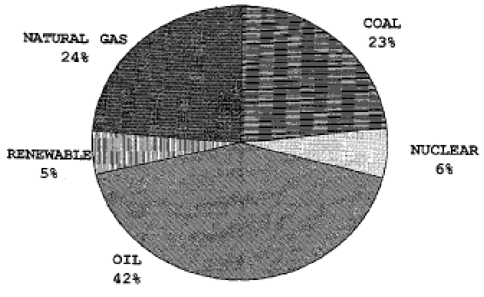
Energy has been the life-blood for continual progress of human civilization. Since the beginning of industrial revolution around two centuries ago, the global energy consumption has increased by leaps and bounds to accelerate the human living standard, particularly in the industrialized nations of the world.

In fact, per-capita energy consumption has been a barometer of a nation's economic prosperity. The USA has the highest living standard in the world. With only 5% of world population, it consumes 25% of total energy. Japan, on the other hand, consumes 5% of total energy with 2% of world population. India and China together, with 38% of world population, consumes only one-tenth of that of USA.

Globally, as indicated in Fig. 1,a, 87% of total energy is generated from fossil fuel (coal, oil and natural gas), 6% is generated in nuclear plants, and the remaining 7% comes from renewable sources (mainly hydro and wind power) [1],[2]. The U.S. energy generation (Fig. 1,b) approximately follows the same pattern [3].



(a) GLOBAL TOTAL ENERGY



(b) US TOTAL ENERGY

Fig. 1 - Energy generation scenario. (a) Global total energy. (b) US total energy.

Fig. 2 shows the electricity generation of USA, Japan, China and India by different types of fuel [4]. In USA, 37% of total energy is generated in electrical form of which 55% comes from coal and 20% comes from nuclear plants. It is interesting to note that China and India generate most of the electricity from coal (74% and 71%, respectively).

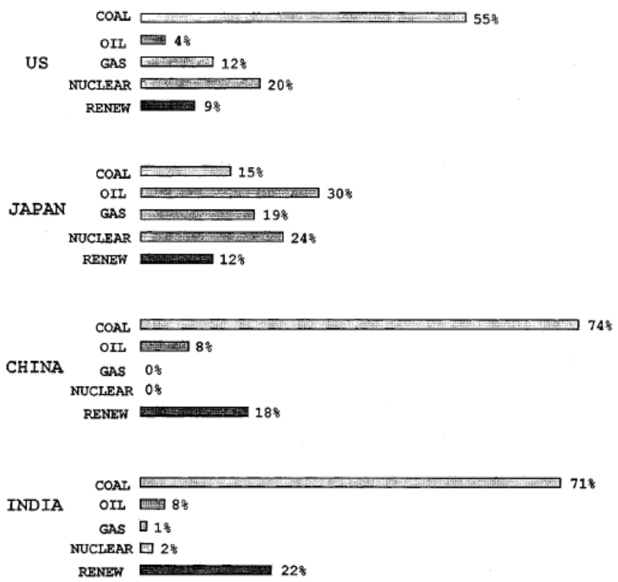


Fig. 2 - Electricity generated by fuel types

Unfortunately, the world has limited fossil fuel and nuclear power resources. Fig. 3 shows the idealized potential energy depletion curves of the world [5]. The world has large reserve of coal. It is then followed by oil, natural gas and uranium fuel, respectively. The natural uranium fuel is expected to last hardly for 50 years. Of course, breeder reactor can generate more nuclear fuel. Oil is expected to last hardly for more than 100 years, and gas for 150 years. However, coal is expected to last for more than 200 years. By energy conservation, the fuel depletion curves can be extended in time. The wind and solar power, not shown in Fig. 3, can be explored extensively. It appears that cheap and abundant energy supply which we are now enjoying will be over in future and our society will be forced to move in an altered direction.

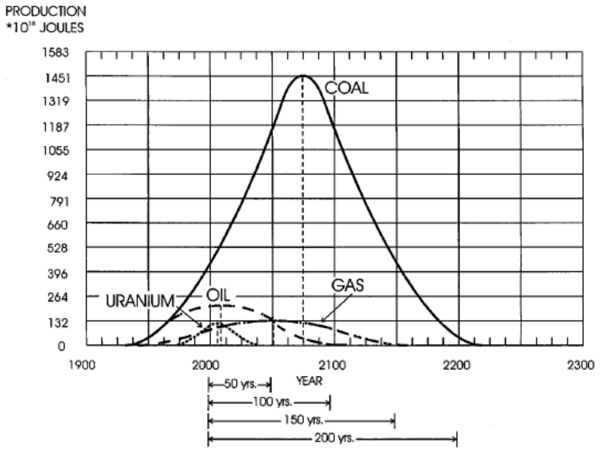


Fig. 3 - Idealized energy depletion curves

## 2.2 Environmental Issues

Unfortunately, environmental pollution and safety problems contributed by increased energy consumption are recently becoming domination issues in our society. Burning of fossil fuels emits gases, such as CO , SO, NO, HC, O and CO, besides generation of fly ash by coal. These gases create environmental pollution problems, such as global warming (green house effect), acid rain and urban pollution.

Global warming (a few degrees in hundred years) may cause melting of polar ice cap and corresponding inundation of low-lying areas of the world. In addition, tthe resulting world climate change may adversely affect our agriculture and vegetation. Of course, preserving the world's rain forests and widespread forestation can alleviate this problem. The acid rain, mainly caused by SO and NO due to coal burning, damages vegetation. Then, of course, there is urban pollution problem mainly by IC engine vehicles.

Fig. 4 compares the present and projected emissions of four different countries, i.e., USA, China, India, and Japan for electricity generation [4]. USA consumes largest amount of electricity, and therefore, emission generated by USA is the largest. Japan is a smaller country and it has much stricter air pollution standard. However, fast developing countries like China and India, mainly dependent on coal, are increasing pollution at a much faster rate. Japan is already facing a problem by coal-generated pollution in near-by China. Environmental pollution is truly a global problem, and the Kyoto conference in 1997 tended to address this problem [6].

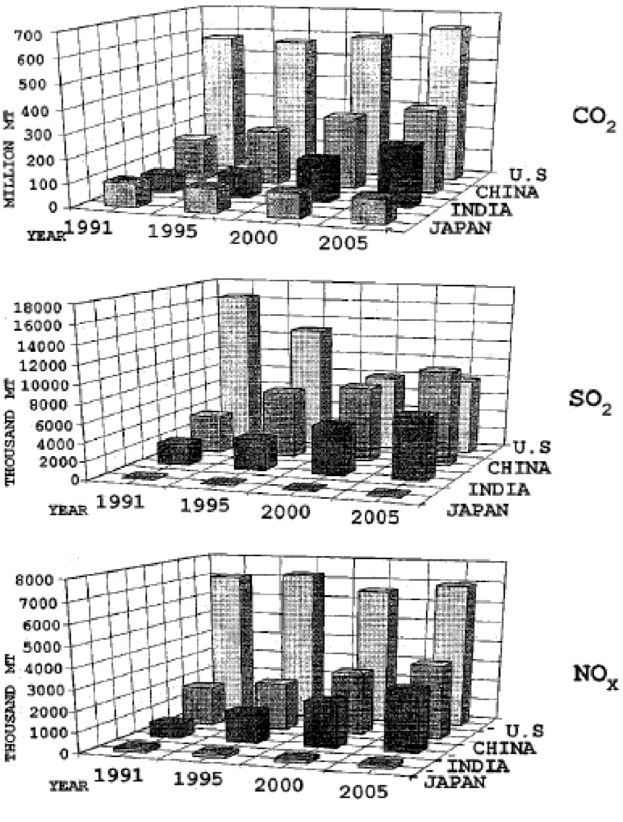


Fig. 4 - Present and projected emissions of selected countries for electricity generation

How can we solve or mitigate the environmental pollution problems? As a first step, all our energy consumption can be promoted in electrical form, and then advanced emission control standards can be applied in central fossil fuel plants. The problems then become easier to handle when compared to distributed consumption of coal, oil and natural gas. As emission control technologies advance, more and more stringent controls can be enforced in central power stations.

Urban pollution can be prevented by widespread use of electric vehicles and subway transportation. Note that wind power, photovoltaics, electric car and subway systems heavily depend on power electronics which will be discussed later. Conservation of energy by more efficient use of electricity, and thus reduction of fuel consumption, is a definite way to reduce pollution esides having economic payoff [7]-[11]. It also helps saving precious fuels for the future. The role of power electronics in energy saving will be discussed later. Unfortunately, availability of cheap energy promotes its wastage. It has been estimated that 33% of total energy is simply wasted in the USA because of consumer negligence [2]. In Japan, energy is typically four times more expensive, and therefore, the urge for energy saving is great.

## 3. IMPORTANCE OF POWER ELECTRONICS

The importance of power electronics in industrial automation, energy conservation and environmental pollution control has already been touched in the previous sections. As the cost of power electronics is falling and the system performance is improving, its applications are proliferating in industrial, commercial, residential, utility, aerospace and military systems. It is expected that this trend will continue with high momentum in this century. Modern computers, communication and electronic systems get life blood from power electronics. Modern industrial processes, transportation and energy systems benefit tremendously in productivity and quality enhancement with the help of power electronics. As mentioned before, the environmentally clean sources of power, such as wind, photovoltaics and fuel cells which will be highly emphasized in future, heavily depend on power electronics [12],[13].

The growing importance of power electronics which is being increasingly visible now-a-days is the energy saving of electrical apparatus by more efficient use of electricity. It has been estimated that roughly *15%– 20% of electricity consumption can be saved* by extensive application of power electronics. According to EPRI (Electric Power Research Institute) estimate, 60%–65% of generated electricity in the USA is consumed in motor drives, and majority of these drives are for pumps and fans. Again, the processes by most of these pump and fan drives can get benefit by variable flow control. The example applications are ID/FD (induced draft/forced draft) fans and boiler feed pumps in fossil power station. Traditionally, variable flow is obtained by throttle control while the driving induction motor runs at constant speed. It can be shown that power electronics controlled variable speed drive with fully open throttle can *save as much as 30% energy* at light load condition. The extra cost of power electronics can be recovered in a period depending on the cost of electricity. Light load machine operation at reduced flux (flux programming control) *can further improve drive efficiency, typically by 20%*. In fact, as the cost of power electronics goes down drastically, the use of variable frequency starter in the front-end of the machine will permit flux-programming control even for constant speed drive applications.

Another example application is variable speed load-proportional air-conditioner/heat pump drive that *can save as high as 30% energy* in comparison with conventional thermostatically-controlled system. Interestingly, because of high energy cost, typically 70% of room air-conditioners in Japanese homes use variable speed drives to save energy. On the other hand, variable speed air-conditioners are practically unknown in the USA because of cheap energy.

It has been estimated that typically 20% of generated energy is consumed in lighting. It is well-known that fluorescent lamps are two to three times more efficient than incandescent lamps. Using high frequency power electronics ballast *can boost fluorescent lamp efficiency typically by additional 20%*. Note that energy saving not only gives economic benefit but the cooling burden also becomes less, and there is the benefit of reduced environmental pollution because of reduced generation.

## 4. ADVANCES IN POWER ELECTRONICS AND DRIVES

### 4.1 Power Semiconductor Devices

Today's progress in power electronics has been possible primarily due to advances in power semiconductor devices. Apart from device evolution, the inventions in converter topologies, PWM techniques, analytical and simulation methods, control and estimation techniques, computers, digital signal processors, ASIC chips, control hardware and software, etc. have also contributed to this progress.

The modern era of solid state power electronics started with the invention of thyristor (or silicon-controlled rectifier) in the late 1950's. Gradually, other devices, such as triac, gate turn-off thyristor (GTO), bipolar power transistor (BPT or BJT), power MOSFET, insulated gate bipolar transistor (IGBT), static induction transistor (SIT), static induction thyristor (SITH), MOS-controlled thyristor (MCT), and integrated gate-commutated thyristor (IGCT) were introduced [14]-[17].

As the evolution of new and advanced devices continued, the voltage and current ratings and electrical characteristics of the existing devices began improving dramatically. *Thyristor*, the general workhorse of power electronics, dominated the first generation of power electronics, typically in the period of 1958–1975. Even today, thyristors are indispensable for handling very high power at low frequency for applications, such as HVDC converters, phase-control type static VAR compensators, cycloconverters and load-commutated inverters. It appears that the dominance of thyristor in high power handing will not be challenged at least in the near future.

*Triac* is basically an integration of anti-parallel thyristors, and is suitable for low frequency resistive type load, such as heating and lighting control. The advent of high power *GTO*'s (Gate Turn-Off thyristor) pushed the force-commutated thyristor inverters, once so popular, into obsolescence. The device continues to grow in power rating (most recently 6000 V, 6000 A) for multi-megawatt voltage-fed and current-fed (with reverse blocking device) converter applications. Slow switching of the device that causes large switching loss restricts its switching frequency to be low (a few hundred Hz) in high power applications. Large dissipative snubbers are essential for GTO converters. Of course, regenerative snubber can be used to improve converter efficiency.

Power *MOSFET*, unlike most other devices, is a majority carrier device. Therefore, its conduction drop is high for higher voltage devices, but the switching loss is low. It is very popular in low voltage high frequency applications, such as switching mode power supplies (SMPS) and other battery-operated power electronic apparatus.

The introduction of *IGBT* (Insulated Gate Bipolar Transistor) in the 1980's was an important milestone in the history of power semiconductor devices. Its switching frequency is much higher than that of BJT, and square SOA (safe operating area) permits easy snubberless operation. The power rating (currently 3500 V, 1200 A) and electrical characteristics of the device are continuously improving. IGBT intelligent power modules (IPM) have been available with built-in gate driver, control and protection for up to several hundred kW power rating. The present (fourth-generation) IGBT's with trench gate technology have conduction drop which is slightly higher than a diode, and much higher switching speed.

*MCT* (MOS-Controlled Thyristor) is another MOS-gated device which was commercially introduced in 1992. The present MCT (P-type with 1200 V, 500 A), however, has limited RBSOA (reverse-biased SOA), and switching speed is much inferior than IGBT. MCT's are being promoted for soft-switched converter applications (will be discussed later) where these inferiorities are not barriers.

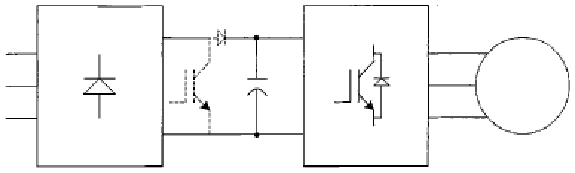
*IGCT* (Integrated Gate-Commutated Thyristor), basically a hard-switched GTO, has been commercially introduced most recently [16] (currently 4500 V, 3000 A). The claimed advantages over GTO are lower conduction drop, faster switching, monolithic bypass diode, snubberless operation, and ease of series operation.

Although silicon has been the basic raw material for power semiconductor devices for a long time, several other raw materials, such as silicon carbide and diamond, are showing significant future promise. These materials have large band gap, high carrier mobility, high electrical and thermal conductivities and strong radiation hardness. Therefore, devices can be built for higher voltage, higher temperature, higher frequency and lower conduction drop. Unfortunately, processing of these materials is very complex.

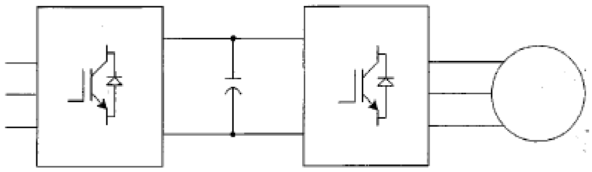
## 4.2 Converters

A converter uses a matrix of power semiconductor switches to convert electrical power at high efficiency. In the 1960's, when inverter-grade thyristors appeared, various types of voltage-fed force-commutated thyristor inverters were introduced. However, these first classes of inverters gradually faced obsolescence because of the advent of self-commutated GTO's and bipolar transistors. Among the PWM techniques, sinusoidal voltage control PWM and hysteresis-band instantaneous current control PWM became very popular. Digital computation intensive space vector PWM (SVM) with isolated neutral loads was introduced in the 1980's. SVM performance is superior to sinusoidal PWM but computation time restricts the upper limit of switching frequency. Because of superior performance, the recent trend is to replace current control PWM by voltage control PWM [18]-[24].

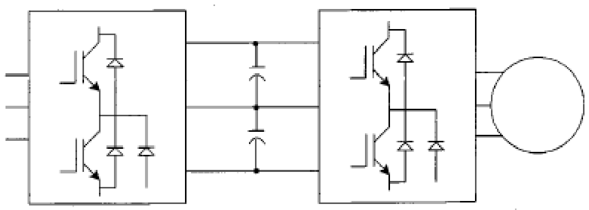
Since PWM inverter can operate both in inversion and rectification modes, the unit can replace the phase-controlled converter on line side solving the harmonics and power factor problems. Fig. 5 shows the progression of modern voltage-fed converter topology. The diode rectifier with boost chopper shapes the line current to be sinusoidal at unity power factor, but it is nonregenerative. A double-sided PWM converter system, in addition, gives regeneration capability which is important for a drive. The topology in this system can be either two-level or three-level (neutral point clamped or NPC). In fact, higher number of levels is also possible. Again, each unit can have half-bridge, H-bridge, or three-phase bridge configuration. Three-level topology, used in high voltage high power applications, gives better harmonic performance without increasing PWM switching frequency.



(a) Diode rectifier - PWM inverter



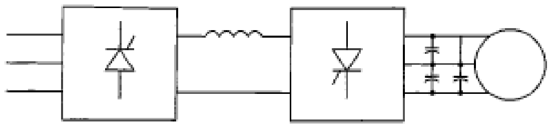
(b) Double-Sided 2-level PWM Converters



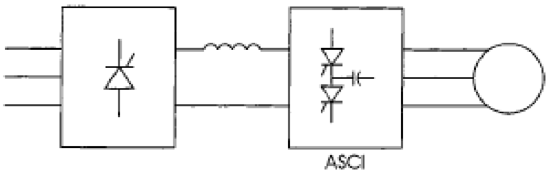
(c) Double-Sided 3-level PWM Converters

Fig. 5 - Progression of voltage-fed converters

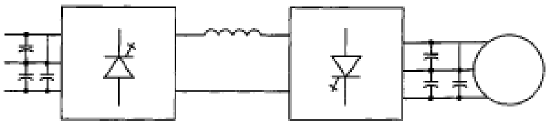
Fig. 6 shows the progression of current-fed converters. Thyristor phase-controlled rectifier/inverter is the most common example in this class. High power (multi-megawatt) load-commutated thyristor inverter (LCI) synchronous motor drives where machines operate at leading power factor are very popular in industry. With induction motor, the same type of converter has been used but with a capacitor bank at the machine terminal for load commutation. Converters can again be multi-stepped (12 or 24 pulse), as mentioned before, to reduce harmonics in line and load currents, but the problem of poor displacement factor remains. Force-commutated current-fed auto-sequential commutated inverters (ASCI) have been used for induction motor drives, but recently, they have become obsolete. Double-sided PWM current-fed converters using self-controlled reverse-blocking devices have essentially the same features as those of voltage-fed topology [Fig. 5(b)]. However, the voltage-fed topology is superior and far more popular in industrial drive applications.



(a)Thyristor Rectifier-load connected inverter WFSM/IM drive



(b) Thyristor rectifier - auto-sequential commutated inverter



(c) Double-Sided PWM Converters

Fig. 6 - Progression of current-fed converters

The traditional converters with self-controlled devices use hard switching principle. Soft switching of devices at zero voltage or zero current (or both) tends to minimize or eliminate device switching loss, thus giving improvement of converter efficiency. Besides, the other advantages are: elimination of snubber loss, improvement of device reliability, less dv/dt stress on machine insulation, reduced EMI problem, and elimination of machine bearing current problem and voltage boost effect at machine terminal with long cable. Soft-switched converters can be generally classified as resonant link dc, resonant pole dc, and high frequency ac link systems. The resonant link dc can be voltage-fed or current-fed type. Soft-switched high frequency ac link system can be resonant (parallel or series) or nonresonant type. Unfortunately, the need of extra components and control complexity are limited now wide market distribution of soft-switched converters.

### 4.3 Electric Drives

Adjustable speed electric drives is still an emerging technology pushed by the evolution in power electronic components and microprocessors. The applications of electric drives get still a broader spectrum of applications like robotics, automation equipment, material handling, electrical vehicles, heating, ventilation and air-conditioning (HVAC), ship propulsion, rolling mills, wind turbines, other appliances and so on [20]-[23]. The world market for adjustable speed drives is still growing rapidly. In the last decade a 10% annual growth in some locations has nearly doubled the market (in value) each 7’th year. Numbers from different markets are shown in Table I [21].

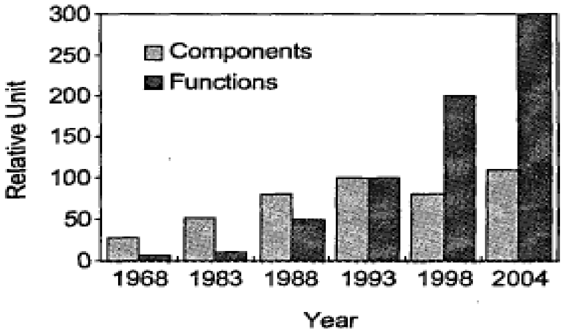
Table I – World market development in adjustable speed drives (Billion Euro) for low voltage up to 160 kW

| **Market** | **1991** | **2002** | **Annual growth** |
|---|---|---|---|
| Europe | 0.44 | 1.08 | 7.7% |
| North America | 0.40 | 0.72 | 5.0% |
| Japan | 0.49 | 0.73 | 3.4% |
| Rest of world | 0.27 | 0.96 | 11.1% |
| Total | 1.60 | 3.49 | 6.7% |

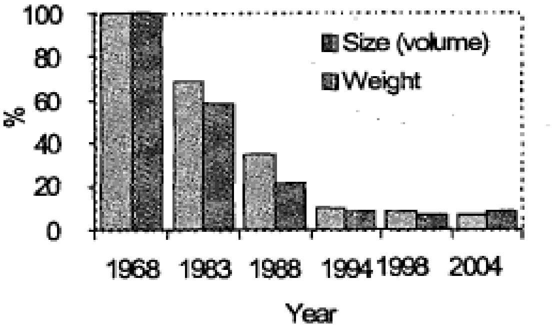
This development combined with **a** global competition and on-going cost reductions helps to drives to become more and more competitive towards other technologies (fixed speed, mechanical, hydraulics etc.), which in turn helps the adjustable speed drive technology to gain ever larger ‘market shares’ compared to the other drive technologies. The main developments responsible for those results are well known, such as semiconductor devices, especially power IGBT’s, and the microcontroller/DSP/ASIC technologies.

The structures of modern adjustable speed drives for the low-power and medium power applications are based now mainly on voltage source converters (Fig. 5), and for high-power applications some topologies of current source converters (Fig. 6) can be used [21].

The general trend is lower cost**,** lower volume and weight, while the. number of functions is steadily increasing as it can be seen in Fig. 7 [21]**.** Furthermore a high level of integration has been seen in order to increase reliability and reduce manufacturing cost.



a)



b)

Fig. 7 – Development of a 4 kW standard drive during the last 35 years. a) number of components and functions; b) size and weight

Table II shows five different control strategies with their different performances and examples of applications [21].

Table II – Overview of different control schemes for adjustable speed drives

| Typical values) | Simple Scalar control | Scalar control with Compen-sation | Voltage Vector Control | Flux-vector Control | Servo-drive |
|---|---|---|---|---|---|
| Speed range | 1:10 (open loop) | 1:25 (open loop) | 1:50 (open loop) | 1:10000 (closed loop) | 1:10000 (closed loop) |
| Static speed error | 10% | 2% | 1% | 0% | 0% |
| Torque rise time | Not available | Not available | 10 ms | < 1 ms | < 1 ms |
| Speed rise time | > 100 ms | > 50 ms | > 20 ms | < 10 ms | < 10 ms |
| Starting torque | Low | Medium | High | High | High |
| Cost | Very low | Low | Medium | High | High |
| Application (typically) | Pumps, Fans | Conveyors | Pack, Crane | Crane, lifts | Robotics |

The basic ideas behind the decentral installation concepts are to save space and reduce installation and commissioning cost. This is achieved by connecting decentrally mounted units directly on a power bus and a communication bus, respectively, and that is all.

A period with increasing cost of fossil fuel as it is seen now will increase the demand for all adjustable speed drives in HVAC (Heating, Ventilation and Air-Condition) applications with the task of energy saving.

The low power drives market demands the maximum of the relationship between functionality and cost. In the last years cost has gone down and it has even been possible to integrate more features. In general the demands from the appliance industry historically are like shown in Fig. 8 [21]. Offering solutions to the low-power market many other issues are of importance: 1) the drive should be easy to adapt to any linevoltage independent on where it is used globally; 2) the drive should be rugged against voltage interruptions; 3) the complete application should be robust and reliable in performance and in hardware, its price should be low enough, etc.

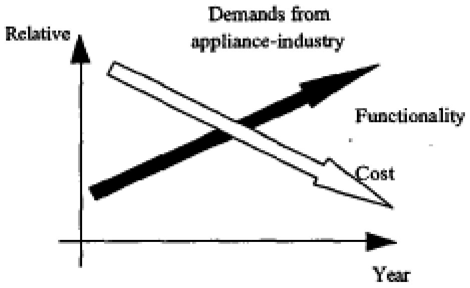


Fig. 8 – Demands from appliance industry to low power drives

There are numerous applications that potentially can benefit from the opportunities offered by variable speed drives. It includes energy saving, added functionality, component cost reduction, system cost reduction and supply chain cost reduction, etc. [19]-[21].

### 4.4 Electrical Machines

Electrical machine is the workhorse in a drive system. Its evolution over the past century has been slow and much less dramatic than that of power semiconductor devices and converter circuits. Electrically, mechanically and thermally, a machine is a very complex system. The advent of modern digital computers, improved modelling, simulation and CAD programs, and availability of new materials have contributed to higher power density, higher efficiency, improved reliability, reduced cost, and improved mechanical and thermal design of the machine in the recent years. Advanced studies related to machine modelling, control, state and parameter estimation, etc. are the exciting R&D topics today for drive system engineers. Although dc machines have been traditionally used for variable speed applications, and yet count as majority today, the advent of solid state variable frequency inverters, improved power semiconductor devices, microprocessors, DSP's, powerful ASIC chips, and advanced control and estimation techniques gradually enhanced the application trend of variable frequency ac drives [19],[20].

Both induction and synchronous machines have been widely used in variable speed drives. The asynchronous induction motor is today's workhorse in industrial drives, and a lot of work is still going on to improve this machine type in different areas such as energy efficiency standards, and the development of inverter motors [21]. One important alternative motor is the permanent magnet synchronous motor, which already today is available for standard drives up to 300 kW in Japan. However, asynchronous motors have a high efficiency in the medium power level, so the most promising, economical power range for permanent magnet synchronous motors is still below 10 kW. Decreasing cost on the rare earth magnet material may of course expand this range.

Synchronous reluctance machines often provide low cost and robust solution, and are suitable for high speed applications. Design of this class of machines has gone through a lot of improvement in recent years.

### 4.5 Control and Estimation

Control and estimation of high performance ac drives have been a very fascinating and challenging area of R & D in the recent years. The advent of powerful microcomputers, digital signal processors, application specific IC's, personal computers, CAD and simulation tools, artificial-intelligence-based techniques, and advancement of control and estimation theories has continuously extended the frontier of control and estimation techniques [25]-[33].

The main basic motor drives control principles, used in industrial drives today, are listed in Table II**,** where some typical performance data are listed.

With the powerful motor control processors available combined with field oriented control, the torque/current control bandwidth can be pushed to the limit determined by the switching frequency of the inverter (all the way to 20 kHz!**).** So with respect to the motor-shaft related performance for high-end drives, it is more or less a cost-reduction problem [21].

In cost sensitive 'open loop' speed controlled drive applications, the availability of more powerful low cost motor control processors will still leave room for the development of advanced speed & torque control methods.

On the advanced application control level, a low cost (and with low power consumption) floating point processor would make it possible to build-in a lot of 'new features' in the drives, which so far mostly have been of academic interest only. This could include fault tolerant control, advanced estimation of process variables, ability to run PC-software modules or artificial intelligence control. In particular, artificial intelligence techniques are showing for advanced ac drive applications [26]-[32].

### 4.6 Pulsewidth Modulation in Converters and Drives

Control of power converters, consisting from the semiconductor switches, is based on principle of modulation of pulse signals, and its efficiency is dependent on the used methods and techniques of pulsewidth modulation (PWM) [34]-[39]. Development of theory and practice of modulation for power converters is an important problem in the field of power electronics and drives.

All varieties of existing methods and techniques of PWM can be grouped into five big groups [34]:

1) modulating-function-based methods;
2) voltage space-vector-based methods;
3) programmed and quasi-programmed methods;
4) feedback and quasi-feedback methods;
5) randomized modulation methods.

Between the existing PWM methods and techniques, voltage space vector modulation is now very popular, particularly for adjustable speed drive systems [20],[34]. So, control of the output signals of three-phase variable-frequency drive converters is now based mainly on the corresponding schemes of space-vector PWM, which is the most suitable for adjustable speed drives.

Fig. 9 and Fig. 10 illustrate the traditional (classical) approach for consideration of different continuous and discontinuous versions of space vector PWM in the undermodulation control mode [34]. In accordance with conventional space-vector approach, the time domain modulation signals are translated to the complex reference voltage vector which rotates in the complex coordinates. So, consideration of space vector PWM methods and techniques is based in this case on the complicated non-linear modulation functions (Fig. 9) together with such sophisticated parameter, as zero-sequence signals (the bold lines in Fig. 9, carrier signals are not shown here).

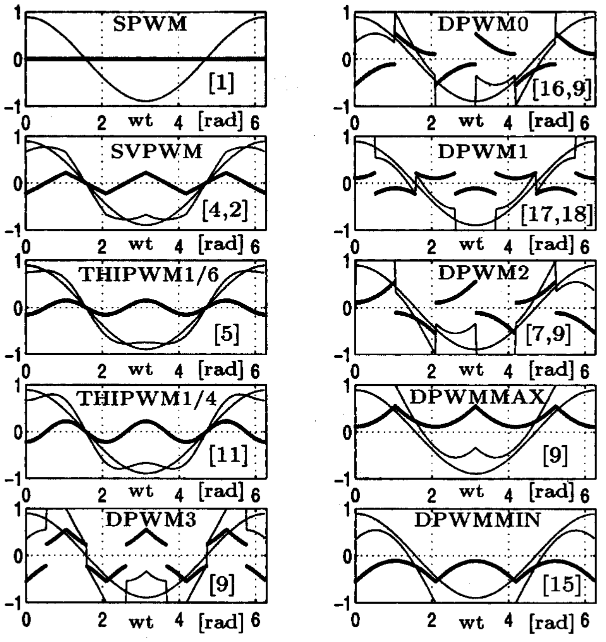


Fig. 9 - Modulation waveforms of the modern PWM methods [34]

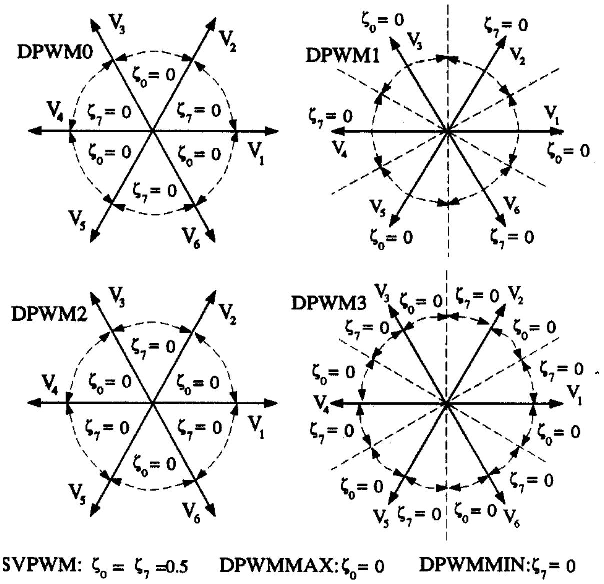


Fig. 10 - Zero-state partitioning of the modern PWM methods

Fig. 10 shows zero-state partitioning for these modern methods of pulsewidth modulation. Mapping the zero-state partitioning of the time domain modulation waves of Fig. 9 onto the vector space domain, the direct digital instrumentation equivalency can be easily obtained [34].

Determination of the duty-cycles for conventional space vector pulsewidth modulation for three-phase voltage source inverters is based on the set of trigonometric control correlations [20],[34].

Classical schemes of space-vector PWM have a set of disadvantages. In paricular, its asynchronous character leads to asymmetrical output voltage waveforms of converters, complicated trigonometric control function lead to big cumputing burden of microprocessor, and also complicated control algorithms are used in this case in the zone of overmodulation.

In order to avoid these disadvantages of classical space-vector modulation, novel method (methodology) of direct synchronised pulsewidth modulation has been recently proposed [35]-[39]. Table III shows basic peculiarities of the proposed methodology of PWM, and it is compared here with conventional voltage space-vector modulation.

Table III – Basic Parameters of PWM Methods

| Control (modulation) parameter | Conventional schemes of vector PWM | Proposed method of modulation | |
|---|---|---|---|
| Operating and max parameter | Operating & max voltage $V$ and $V_m$ | Operating & maximum fundamental frequency $F$ and $F_m$ | |
| Modulation index $m$ | $V/V_m$ | $F/F_m$ | |
| Duration of sub-cycles | $T$ | $\tau$ | |
| Center of the $k$-signal | $\alpha_k$ (angles/degr.) | $\tau(k-1)$ (sec) | |
| Switch-on durations | | Algebraic PWM | Trigonometric PWM |
| | $T_{ak} = 1.1mT[\sin(60^0 - \alpha_k) + \sin\alpha_k]$ | $\beta_k = \beta_1[1 - A \times (k-1)\tau F K_{ov1}]$ | $\beta_k = \beta_1 \times \cos[(k-1)\tau K_{ov1}]$ |
| | $t_{ak} = 1.1mT\sin\alpha_k$ | $\gamma_k = \beta_{i-k+1}[0.5 - 6(i-k)\tau F]K_{ov2}$ | $\gamma_k = \beta_{i-k+1}[0.5 - 0.9\tau n(i-k)\tau]K_{ov2}$ |
| | $t_{bk} = 1.1mT \times \sin(60^0 - \alpha_k)$ | $\beta_k - \gamma_k$ | $\beta_k - \gamma_k$ |
| Switch-off states (zero voltage) | $t_{0k} = T - t_{ak} - t_{bk}$ | $\lambda_k = \tau - \beta_k$ | |
| Special parameters providing synchronization of the process of PWM | | $\beta'' = \beta_1[1 - A \times (k-1)\tau F K_{ov1}]K_s$<br>$\lambda' = (\tau - \beta'') \times K_{ov1}K_s$ | $\beta'' = \beta_1 \times \cos[(k-1)\tau K_{ov1}]K_s$<br>$\lambda' = (\tau - \beta'') \times K_{ov1}K_s$ |

Fig. 11 and Fig. 12 illustrate the proposed method more in details. As it is shown in Fig. 11, the method is based on special simple representation of switching state sequences, which are presented in Fig. 11 for typical schemes of continuous and discontinuous PWM. Also two simple functions (Fig. 12) connecting relative width of active switching states with their position inside the $60^0$-clock-intervals, are basic for determination of parameters of pulse signals. These functions, as it is shown in Fig. 12, can be easily approximated by the corresponding linear functions, which are good for fast computation during real-time realization of control algorithms.

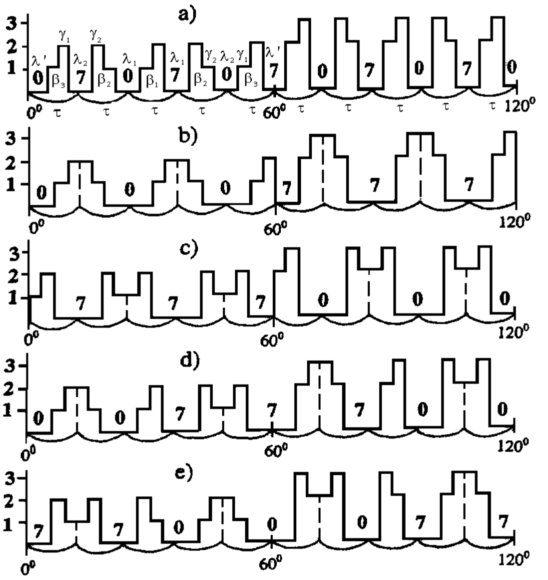


Fig. 11 - Switching state sequences for typical PWM schemes: a) CPWM; b) DPWM0; c) DPWM2; d) DPWM3; e) DPWM1 [35]

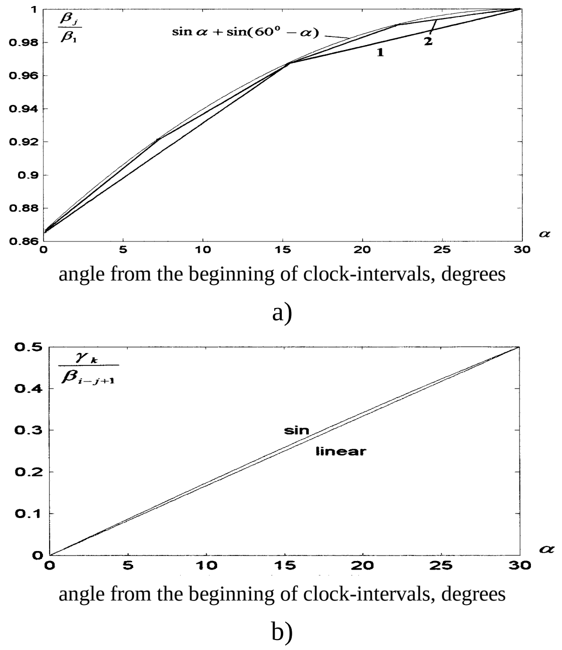


Fig. 12 - Variation of the functions for total switch-on durations (a), and of the minor part of the total switch-on durations (b)

The proposed methodology of direct synchronised pulsewidth modulation is characterised by the following properties and peculiarities [35]-[39]:

- it provides continuous smooth synchronization of the output voltage waveforms of converters, and its spectra do not contain even harmonics and combined harmonics (sub-harmonics), which is especially important for the systems with increased power rating;

- algebraic versions of the proposed PWM algorithms provide increased computing effectiveness of control systems in comparison with the trigonometric-based algorithms of standard space-vector modulation;

- it provides high quality linear control of the fundamental voltage of converters in zone of overmodulation;

- the proposed methodology is characterised by the simplicity and physical clearness, that can be used in teaching and learning.

## 5. CONCLUSIONS AND PROGNOSIS

As the conclusions of the presented review it may be possible to give some prognosis for the future trend in power electronics. First, it can be predicted with confidence that power electronics applications will spread everywhere — in every phase of industrial, commercial, residential, utility, transportation, aerospace and military environments. The main reason is drastic cost and size reduction with improvement of performance and reliability of future power electronics systems.

Besides general process applications, energy saving will be the important motivation, as mentioned before. As our energy demand tends to grow further to improve our living standard, more rigid environmental regulations will tend to drive up the energy cost, and thus will promote more conservation of energy.

With the present research trend, the cost of photovoltaic energy will come down substantially. Environmental regulations will promote photovoltaic and wind energy extensively. The trend in wind energy is already evident. Our future hope of environmentally clean and safe fusion energy appears very uncertain at this point.

The battery technology is expected to have a breakthrough promoting widespread applications of electric and hybrid vehicles in future. The scarcity of standard engine fuels (and correspondingly high cost), and the urge to minimize urban pollution problem, are bound to promote EV/HV in the market eventually even with the expensive and bulky batteries.

Of course, extensive R & D will significantly improve other energy storage and power devices. Silicon carbide, and ultimately the diamond power semiconductor devices, will usher another renaissance in power electronics — pushing the silicon material essentially into control microelectronics only. High frequency, high temperature, low conduction drop and improved radiateon hardness of the new power devices will boost efficiency of the increasingly popular voltage-fed converters.

It can be easily predicted that phase-controlled converters which are currently so popular on utility line will eventually phase extinction, thus solving the power quality and power factor problems permanently. High power multi-terminal HVDC systems, rolling mill drives, pump and compressor drives, static VAR compressors in flexible ac transmission (FACT) systems will use voltage-fed inverters with these devices.

We expect that the converter technology will have the similar trend as VLSI technology, and the present generation of converter circuit designers will tend to disappear. Future converters will have automated computer-aided design and built as integrated and intelligent building blocks, similar to the trend of microchips. Future power electronics R & D activity will be essentially confined to devices and systems.

With drastic cost reduction, almost every ac machine (both variable and constant speed) will be eventually coupled with a front-end converter. Variable frequency starting (solid state starter) of a constant speed machine will solve power quality problem as well as improve operational efficiency at light-load by flux programming control. At the lower end of power, “intelligent machines” will be built with integrated converter and control in the same frame.

It appears that switched reluctance drives will not be able to stand in competition with induction and permanent magnet machine drives for general industrial applications. Its application will be restricted to a few specialized applications, as mentioned before. Reduced cost of high energy magnet and improved efficiency will promote increased volume of permanent magnet machine drives, particularly when energy cost increases.

Considering the present trend, it appears that the popular volts/Hz control of ac drives will disappear and sensorless vector control will be universally accepted, except for high precision speed and position control systems that require near zero speed operation. The simplicity of volts/Hz control and complexity of sensorless vector control with powerful DSP are essentially transparent to the user.

Pulsewidth modulation strategies and methodologies will have continuous development, with its effective dissemination to perspective topologies of converters and drives. Advanced intelligent control and estimation based on fuzzy logic and neural network will find dramatically increasing acceptance in power electronic systems.

## REFERENCES

[1] B.K. Bose, “Energy, environment and advances in Power Electronics,” *IEEE Trans. Power Electronics*, vol.15, no.4, pp.688-701, July 2000.

[2] G.R. Davis, “Energy for planet earth,” *Scientific American*, pp.1–10, 1991.

[3] U.S. Department of Commerce, *Statistical Abstract of the United States*, 114th ed., 1998.

[4] S. Rahman and A.D. Castro, “Environmental impacts of electricity generation: A global perspective,” *IEEE Trans. Energy Conv.*, vol.10, pp.307–313, June 1995.

[5] J.R. Roth, “Long term global energy issues”, in *Industrial Plasma Engineering*, Institute of Physics Publication, Philadelphia, PA, vol.1, 1995.

[6] R.L. Kane *et al.*, “Global climate change: A discussion of major uncertainties,” in *Proc. Amer. Power Conf.*, vol.53-1, Apr. 1991, pp.646–652.

[7] J. Jaydev, “Harnessing the wind,” *IEEE Spectrum*, pp.78–83, Nov. 1995.

[8] W. Sweet, “Power and energy,” *IEEE Spectrum*, pp.62–67, Jan. 1999.

[9] E.H. Lyson, “Photovolts for villages,” *IEEE Spectrum*, pp.34–39, Oct. 1994.

[10] B.K. Bose, *Power Electronics and Variable Frequency Drives*. New York: IEEE Press, 1997.

[11] --------, “Power electronics—A technology review,” *Proc. IEEE*, vol.80, pp.1301–1304, Aug. 1992.

[12] B.K. Bose, “Power electronics and motion control — Technology status and recent trends,” *IEEE Trans. Ind. Applicat.*, vol.29, pp. 902–909, Sept./Oct. 1993.

[13] --------, “Trends in power electronics and drives,” in *Proc. Conf. Ind. Drives*, 1998.

[14] --------, “Evaluation of modern power semiconductor devices and future trends of converters,” *IEEE Trans. Ind. Applicat.*, vol.28, pp.403–413, Mar./Apr. 1992.

[15] B.J. Baliga, “Trends in power semiconductor devices,” *IEEE Trans. Electron Devices*, vol.43, pp.1717–1723, Oct. 1996.

[16] P.K. Steimer *et al.*, “IGCT—A new emerging technology for high power low cost inverters,” in *Proc. IEEE IAS’1997*, pp.1592–1599.

[17] B.J. Baliga, “Power discrete devices: Future structures and materials,” in *Proc. IEEE FEPPCON III*, 1998, pp.275–280.

[18] D. Divan and D. Boroyevich, “Future converters, circuits, and system integration,” in *Proc. IEEE FEPPCON III*, 1998, pp.327–333.

[19] B.K. Bose, “Energy, environment, and progress in power electronics,” in *Proc. Jpn. IEE/IAS Meeting, Invited Lecture*, 1997.

[20] B.K. Bose, *Modern Power Electronics and AC Drives*, Prentiss Hall, NJ: 2002.

[21] F. Blaabjerg and P. Thoegersen, “Adjustable speed drives – future challenges and applications,” in *Proc of the Int’l Power Electronics and Motion Control Conf.*, 2004, pp.36-45.

[22] H. Okayama *et al.*, “Large capacity large high performance three-level GTO inverter systems for steel main rolling mill drives,” in *Proc. IEEE IAS’1996*, pp.174–179.

[23] T. Ohmae and K. Nakamura, “Hitachi’s roles in the area of power electronics for transportation,” in *Proc. IEEE IECON’1993*, pp.714–719.

[24] T.S. Wu *et al.*, “A review of soft switched dc-ac converters,” in *Proc. of IEEE IAS’1996*, pp.1133–1143.

[25] B.K. Bose, “High performance control and estimation in ac drives,” in *Proc. IEEE IECON’1997*, pp.377–385.

[26] --------, “Expert system, fuzzy logic, and neural network applications in power electronics and motion control,” *Proc. IEEE*, vol.82, pp.1303–1323, Aug. 1994.

[27] M.G. Simoes, B.K. Bose, and R.J. Spiegel, “Design and performance evaluation of a fuzzy logic based variable speed wind generation system,” *IEEE Trans. Ind. Applicat.*, vol.33, pp.956–965, July/Aug. 1997.

[28] M.G. Simoes and B.K. Bose, “Neural network based estima-tion of feedback signals for a vector controlled induction motor drive,” *IEEE Trans. Ind. Appl.*, vol.31, pp.620–629, 1995.

[29] G. Kaplan, “Industrial electronics,” *IEEE Spectrum: Technologies 2000*, pp.104–105, Jan. 2000.

[30] K. Warwick, G.W. Irwin, and K.J. Hunt, *Neural Networks for Control and Systems*. London, U.K.: IEE, 1992.

[31] B.K. Bose and N.R. Patel, “A sensorless stator flux oriented vector controlled motor drive with neuro-fuzzy based performance enhancement,” in *Proc. IEEE IAS’1997*, pp.393–400.

[32] L.E.B. da Silva, B.K. Bose, and J.O.P. Pinto, “Recurrent neural network based implementation of a cascaded low-pass filter used in stator flux synthesis of vector-controlled motor drive,” *IEEE Trans. Ind. Electron.*, vol.46, pp.662–665, Apr. 1999.

[33] P. Vas, *Sensorless Vector and Direct Torque Control*. Oxford, U.K.: Oxford Univ. Press, 1998.

[34] D. G. Holmes and T. A. Lipo, *Pulse Width Modulation for Power Converters. Principles and Practice*. IEEE Press, NY, 2003.

[35] V. Oleschuk and F. Blaabjerg, “Direct synchronized PWM techniques with linear control functions for adjustable speed drives”, in *Proc. IEEE APEC’2002*, pp.76-82.

[36] V. Oleschuk, F. Blaabjerg and B.K. Bose, “Analysis and comparison of algebraic and trigonometric methods of synchronous PWM for ac drives”, in *Proc. IEEE PESC’2002*, pp.1439-1444.

[37] S.K. Mondal, B.K. Bose, V. Oleschuk and J. Pinto, “Space Vector Pulse Width Modulation in Three-Level Inverter Extending Operation into Overmodulation Region”, *IEEE Trans. Power Electron.*, vol.18, no.2, pp.604–611, Apr. 2003.

[38] V. Oleschuk, F. Blaabjerg and B.K. Bose, “Triphase cascaded converters with direct synchronous pulsewidth modulation”, *Automatika*, vol. 44, no. 1-2, pp. 27-33, 2003.

[39] V. Oleschuk, A. Stankovich, A. Sizov and E. Yaroshenko, “Analysis of control regimes of three-level inverters with synchronized modulation,” in *Proc. IEEE ISIE’2005*, pp.663-668.

**Bimal K. Bose** (*Life Fellow, IEEE*) received the B.E. degree from the Bengal Engineering College, Calcutta, India, the M.S. degree from the University of Wisconsin, Madison, and the Ph.D. degree from Calcutta University, Calcutta, in 1956, 1960, and 1966, respectively.

He currently holds the Condra Chair of Excellence in Power Electronics at the University of Tennessee, Knoxville, where he is responsible for organizing the power electronics teaching and research program for the last fifteen years. He is also the Distinguished Scientist of EPRI-Power Electronics Applications Center, Knoxville; and also Honorary Professor of four foreign universities. He has served as a consultant in more than ten industries.

Research interests of Dr. B.K. Bose extend across the whole spectrum of power electronics, and specifically include power converters; ac drives; microcomputer control; EV drives; and expert system, fuzzy logic and neural network applications in power electronics and drives.

He has published more than 180 papers, and holds 21 U.S. patents. He is author and editor of six books that include two bestsellers *Power Electronics and AC Drives* (NJ: Prentice-Hall, 1986) and *Modern Power Electronics and AC Drives* (NJ: Prentice-Hall, 2002), which have been translated into Japanese, Chinese, and Korean, and is widely used as a graduate level text book.

Dr. Bose received the IEEE Industry Applications Society’s Outstanding Achievement Award in 1993, IEEE Industrial Electronics Society’s Eugene Mittelmann Award in 1994, IEEE Region 3 Outstanding Engineer Award in 1994, IEEE Lamme Gold Medal in 1996, IEEE Continuing Education Award in 1997, the IEEE Millennium Medal in 2000, and also a number of IEEE prize paper awards. He is listed in Marquis *Who’s Who in America*.

Dr. B.K. Bose has served the IEEE in various capacities, and has served also in a large number of other national and international professional organizations, including Distinguished Lecturer positions.

**Valentin Oleschuk** received the M.S. degree from Kishinev Polytechnic Institute (1969), Candidate of Sc. (Ph.D) degree from Leningrad Institute of Fine Mechanics and Optics (1980), D.Sc. degree from Institute of Electrodynamics of the National Academy of Sc. of Ukraine (1999) and Dr.Habilitat of Sc. degree from the Superior Sc. Qualification Board of Moldova (2000), all in Electrical Engineering.

From 1990 he is Director of the Automated Electric Drives Laboratory of the Institute of Power Engineering of the Academy of Sciences of Moldova. His research interests include control and modulation methods and techniques for perspective topologies of power electronic converters and adjustable speed induction motor drives.

Dr. V. Oleschuk hold also positions of Visiting Researcher and Visiting Research Professor in University of Quebec at Trois-Rivieres (1994, 1995), The University of Tennessee at Knoxville (1997, 1998, 2002), Aalborg University, Denmark (2001-2002), Northeastern University (Boston, 2005), Politecnico di Torino (2005).

Dr. V. Oleschuk authored and co-authored two books and more than 150 publications on power electronics and drives, including 27 publications in the IEEE transactions and proceedings, and also of 89 parents and authors certificates in this field. The results of his research have been presented at the Int’l sc. forums in more than 30 countries. He also presented invited lectures on the topic of his investigations in top universities of Canada, Hungary, Italy, Poland, Puerto-Rico, USA.

During 1994 – 2005 he served as Principal Investigator of 10 Int’l Sc. Projects, including four NATO Collaborative Research, Linkage and Fellowship Projects, two Projects of the US Civilian R&D Foundation (CRDF), Project of the National Research Council of the USA, and Marie Curie Int’l Fellowship Project of FP6 Program of EU.

**Alexandr Sizov** graduated from Kishinev Polytechnic Institute in 1971 (Electrophysical Department). From 1980 he works in the Institute of Power Engineering of the Academy of Sciences of Moldova. He holds now position of Scientific Collaborator. He is author and co-author of about 40 publications and 10 patents in the field of power electronics and drives. His research interests include elaboration, modelling and simulation of control algorithms and control systems for power electronic converters and drive systems.

**Evgeni Yaroshenko** graduated from Kishinev Polytechnic Institute in 1972 (Electrophysical Department). After graduation he works in the Institute of Power Engineering of the Academy of Sciences of Moldova. From 2001 E. Yaroshenko holds position of Scientific Secretary of the Institute, and also works partly as Scientific Collaborator of the Laboratory of the Automated Electric Drives. He is author and co-author of more than 40 publications and of 8 patents. His research interests are connected with elaboration, modelling, simulation and implementation of modern topologies of adjustable speed drive systems.