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PROGRESSION OF POWER ELECTRONICS – ITS IMPACT ON ENERGY AND ENVIRONMENT

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Abstract: Power electronics has gone through rapid technological evolution in the recent years, and its applications are fast expanding in industrial, commercial, residential, military, aerospace and utility environments. Many innovations in power semiconductor devices, converter topologies, analytical and simulation techniques, electrical machine drives, and control and estimation methods have contributed this advancement.The frontier of this complex and interdisciplinary technology has been further advanced by the artificial intelligence (AI) techniques, such as fuzzy logic, neural networks and genetic algorithm, thus bringing more challenge to power electronic engineers. In the global industrial automation, energy generation, 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 issues. The mitigation of energy and environmental problems is then discussed with particular emphasis of power electronics applications. A brief but comprehensive review of recent advances in power electronics is incorporated in the paper.

Key Words: Energy, power electronics, drives, environment, converters, devices

1. Energy Scenario

Energy is the life-blood for continual progress of human civilization. Since the beginning of industrial revolution in Brittain around two centuries ago, the global energy consumption has increased dramatically to accelerate our 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 (6 billions), 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 2.5% of total energy. The U.S. living standard is undoubtedly the envy of the whole world.

Globally, around 87% of total energy is generated from fossil fuel (coal-28%, oil-38% and natural gas-21%), 6% is generated in nuclear plants, and the remaining 7% comes from renewable sources (hydro, biomass, geothermal, solar and wind). The U.S. energy scenario essentially follows the same pattern. Approximately, 42% of U.S. energy comes from oil, most of which is consumed in automobile transportation. Currently, USA imports 56% oil from outside, and this dependency on foreign oil causes serious problems for USA.

In USA, 37% of total energy is generated in electrical form of which 55% comes from coal, 20% comes from nuclear plants, 12% comes from natural gas, and the remaining 9% comes from renewables. The respective distribution for Japan is 15%, 24%, 19% and 12%. Japan does not have natural energy resources. Therefore, it has to depend heavily on nuclear energy and imported oil. It is interesting to note that the world's two developing countries China and India with largest population generate most of the electricity from coal (74% and 71%, respectively).

Unfortunately, the world has only limited fossil fuel and nuclear energy resources. The coal reserve in the world is large. 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. With the present rate of consumption, 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. How can we operate our large fleet of automobiles, ocean liners and aeroplanes when oil gets totally depleted? Of course, fossil fuels can be converted to alternate forms which often can be expensive. Will the wheels of our civilization will come to a halt beyond the 22nd century when fossil and nuclear fuels become totally exhausted? By extensive energy conservation, the fuel depletion can be extended in time. The renewable energy source, such as wind and solar power which is not mentioned above, can be explored extensively. Can we expect a break-through in fusion power to solve our future energy needs? Unfortunately, in spite of prolonged and expensive research, fusion power has not yet shown any practical sign of future promise. The U.S. Department of Energy has recently down-scaled fusion research in the laboratories. It appears that cheap and abundant energy supply which we are now enjoying will be over in future and we will be forced to adjust our life-style with shortage of energy.

2. Environmental Problems

Unfortunately, environmental pollution and safety problems contributed by increased energy consumption are recently becoming dominating issues in our society. Nuclear power plants have potential safety problems. Besides, nuclear plant waste remains radioactive for thousands and possibly millions of years. We do not know how to satisfactorily dispose of the nuclear waste except to bury it deep in the underground**.** The U.S. society vehemently opposes expansion of nuclear power in spite of having stringent safety standards imposed by Nuclear Regulatory Commission (NRC). Nuclear power expansion has stopped in USA from 1970's after accident in three-mile island plant. Anti-nuclear slogan has spread in Europe and the rest of the world.

Burning fossil fuels emit gases, such as CO_2 , SO_2, NO_x, HC, O_3 and CO, besides generation of fly ash by coal. Accumulation of CO_2 in atmosphere causes global warning problem (green house effect) which might eventually melt polar ice cap causing widespread inundation of low-lying areas of the world. In addition, the resulting world climate change may adversely affect agriculture and vegetation on earth. Of course, preserving the world's rain forests and widespread forestation can alleviate this problem. The acid rain, mainly caused by SO_2 and NO_x due to coal burning, damages vegetation. Finally, of course, there is serious urban pollution problem mainly due to automobile transportation.

It is interesting to compare air pollution trends of four different countries – USA, China, India and Japan. USA consumes largest amount of electrical energy in the world, and therefore, CO_2, SO_2 and NO_x emission is the largest in USA. Japan is a small country and it has much stricter air pollution standard. However, fast developing countries like China and India which are mainly dependent on coal, are increasing pollution at a faster rate. This is a serious problem, particularly for Japan, because polluted air from China easily affects Japan in spite its rigorous emission standard. Environmental pollution is truly a global problem, and the Kyoto conference in 1997 attempted to address this problem.

How can we solve or mitigate our environmental pollution problems? As a first step, all our energy consumption can be promoted to be in electrical form. Then, advanced emission control standards can be applied to central fossil fuel plants. The problem then become easier to handle when compared to distributed consumption of coal, natural gas and oil (e.g., automobile transportation). As emission control technologies advance, more and more stringent controls can be enforced in central power stations. Of course, CO_2 problem remains essentially unsolved by this approach. Considering the emission problems of fossil fuels, there is a strong feeling in some circles that nuclear energy has a possibility of comeback in future in spite of its safety and waste disposal problems. Of course, France and Japan (where considerable fraction of energy comes from nuclear plants) remain proponents of nuclear power.

3. Renewable Energy Scenario

Among the renewable energy sources, wind and photovoltaic show excellent promise for the future. They are safe, environmentally clean and have abundant availability in nature. Besides, the operating and maintenance costs are very low. The wind energy is the cheapest and the technology has dramatically advanced in the last decade. It has been estimated that if only 10% of raw wind energy can be utilized, the whole world's electricity needs can be met. The recent technology advances in variable speed horizontal wind turbines (up to 1.6 MW capacity), power electronics and variable speed drives accompanied with substantial cost reduction are promoting large expansion of wind energy programs all over the globe, particularly in USA, Europe, China and India. The current capital cost of wind power is typically $1.00/W and the corresponding energy cost is 5 to 6 cents per kWh, and this is competitive with natural gas generated energy cost. Large new wind farms produce electricity at 3 to 4 cents per kWh (with tax credit) which is competitive with that of conventional power. The average consumer electricity cost is around 7 cents per kwh in USA. Currently, Germany is the world leader in wind power capacity which is then followed by USA and Spain, respectively. However, in Denmark, 13% (largest) of total electricity need is met by wind power which is expected to increase up to 40% by 2030 by the new ambitious offshore wind exploration program. In USA, on the other hand, only 1% of electricity consumption is met by wind. The U.S. Department of Energy (DOE) has a projection that by 2020, this will rise to 5%. The U.S. wind potential is so high that it can easily supply more than twice the electricity need. Interestingly, North Dakota alone has two and a half times wind potential compared to that of Germany. Again, the state of Texas, which is just behind North Dakota, has enough wind potential to meet 40% of total U.S. electric demand. European Wind Energy Association predicts that with current rate of expansion, 10% of world electricity needs will be met by wind power by 2020. It should be noted however that wind energy alone can not satisfactorily meet a nation's energy resource because of its sporadic availability. It must be backed by other energy sources.

In comparison with wind energy, photovoltaic system has the advantage that it is purely static. However, currently, it is very expensive. PV capital cost today is typically $5.00/W and the energy cost is 20 cents per kWh. The cost is expected to come down substantially in future with the present rate of research. As mentioned before, both wind and PV energy availability are statistical in nature, and therefore, often requires back-up energy sources.

Wind and solar power are particularly attractive for people of the emerging countries who are not tied to electric power grids. It has been estimated that currently around two billion people (33% of world population) are isolated from power grids. Again, after the September 11 terrorist attacks, there is a widespread fear that they will next make our nuclear power plants and power grids as targets. If that happens, the widespread shutdown of electrical power will paralyze the whole nation. In this perspective, should we try to go back to decentralized and dispersed energy sources emphasizing more on wind and photovoltaics?

4. Electric and Hybrid Vehicles

Environmental pollution problem, particularly the urban pollution, can be solved by widespread use of electric/hybrid vehicles and subway electric transportation. Currently, oil conservation as engine in cars. In a fuel cell, hydrogen is the basic fuel which can be derived from gasoline well as environmental pollution control are the main motivating factors for worldwide EV/HV programs. In 1990, California Air Resource Board (CARB) established rules (with several amendments thereafter) that mandates 10% of all vehicles sold in California by 2004 must be zero emission vehicles. California mandate made reverberations not only in the other states of USA but in Europe and Japan also. Considering the potential importance of electric and hybrid vehicles, in September 1993, the U.S. President along with the "big three" automakers, declared the PNGV (Partnership for Next Generation Vehicles) program with the goal of producing state-of-the-art hybrid vehicle by the year 2004. The vehicle should have fuel efficiency (80 miles/gallon) three times that of present IC engine vehicles, range of 380 miles, useful life of 100,000 miles and very low emission (0.125 HC/1.7 CO/0.2 NO_x gms/mile). Of course, the vehicle should be cost-effective and acceptable by customers. The PNGV program has spurred a lot of R & D activity in energy storage and power devices for HV. The energy storage devices include different types of battery, flywheel and ultra-capacitors, and the power devices include IC engine, diesel engine, gas turbine and fuel cell. Prominent auto manufacturers in the world have ambitious programs to develop fuel cell cars that propose to replace the IC or natural gas with the help of on-board reformer or pure H_2 can be used in liquid or gaseous form. The design of a compact low-cost reformer for automotive application is a formidable challenge. Hydrogen and oxygen of air react through an electrolyte to produce electricity which can be used to drive vehicle motor through power electronic system. Fuel cell is a static device, has high efficiency (50%) and is environmentally clean. However, fuel cells are yet very expensive, bulky and the response is somewhat sluggish. Widespread R & D are needed to solve these problems. Currently, only PAFC (Phosphoric Acid Fuel Cell) is available commercially which costs \$5,600/kW (i.e., \$560,000 for a 100 kW plant on EV). Dramatic cost and size reduction of fuel cell so that it can be competitive for vehicle transportation remains yet very uncertain. Hydrogen has been proposed to be mass-manufactured from water with the help of abundantly-available but sporadic wind energy. Of course, hydrogen can also be used as fuel in many energy systems. Economy of such fuel cell cars with multiple energy conversion remains questionable.

5. Importance of Power Electronics

The importance of power electronics in global industrial automation, energy systems, energy conservation and environmental pollution control is tremendous. As the cost of power electronics is falling and system performance is improving, its applications are proliferating in different applications. In industrial process applications, it permits higher productivity with precision product quality. The environmentally clean renewable energy systems, as mentioned before, are heavily dependent on power electronics. Fuel cell energy systems for which we are giving so much future emphasis also depend on power electronics. In transportation systems, particularly in electric and hybrid vehicles, power electronics constitutes a dominant component. In fact, this is perhaps the only component in EV/HV which can be considered to have somewhat mature technology. Power electronics permits bulk storage of electrical energy (battery, SMES, flywheel or pumped storage) that permits optimum and reliable utilization of utility system energy resources. Besides, modern computers, communication and electrical and electronic systems get life-blood from power electronics.

The importance of power electronics, where it is being increasingly visible nowadays, is in 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. Approximately, 60% of generated electricity in the USA is consumed in motor drives, and 75% of them are for pumps and fans. The processes by most of these pump and fan drives can benefit and save energy by variable speed power electronics controlled motor drives. The extra cost of power electronics can be recovered in a period depending on the cost of electricity. An example application is variable speed load-proportional air-conditioner/heat pump drive that can save up to 30% energy. It is estimated that 20% of generated energy is consumed in lighting. Using high frequency fluorescent lamps with the help of power electronics can save 20% energy over the conventional fluorescent lamp. Note that energy saving not only reduces consumer electric bill but the cooling burden on equipment becomes less (simplifying the system design), and there is the benefit of reduced environmental pollution because of reduced energy generation.

6. Progression of Power Semiconductor Devices

The progress in power electronics today has been possible primarily due to advances in power semiconductor devices. Of course, apart from device evolution, the inventions in converter topologies, PWM techniques, control and estimation techniques, digital signal processors, ASIC chips, control hardware and software, etc. have also contributed to this advancement. Modern era of solid state power electronics began with the advent of thyristor (or silicon controlled rectifier) in the late 1950's. Gradually, other devices, such as triac (1958), gate turn-off thyristor (GTO)(1958), bipolar power transistor (BPT or BJT) (1975), power MOSFET (1975), insulated gate bipolar transistor (IGBT)(1985), static induction transistor (SIT) (1975) and integrated gate-commutated thyristor (IGCT)(1987) were introduced. As the evolution of new and advanced devices continued, the voltage and current ratings and electrical characteristics of the existing devices began improving dramatically. In fact, the device evolution along with converter, control and system evolution was so spectacular in the last decade of 20th century, we define it as the "decade of power electronics".

Thyristors are used for high power low frequency applications, such as HVDC systems, static phase-control type static VAR compensators, cycloconverters and load-commutated inverter (LCI) synchronous machine drives. Currently, devices are available with 8000 V and 4000 A ratings**.** ABB recently introduced a monolithic thyristor AC switch tha has the voltage ratings of 2.8 KV – 6.5 KV and current ratings of 3000 – 6000 A. The advent of large GTOs pushed the thyristor voltage-fed inverters from the market. Currently, GTOs are available with 6000 V, 6000 A (Mitshibishi) ratings for large voltage-fed inverter applications. Power MOSFET has grown in rating, but it's primary popularity is in high-frequency switching mode power supply and portable appliances. In 1998, Infineon Technology, Germany introduced CoolMOS (600 V) with only 20% conduction loss and reduced switching loss. However, there is difficulty of using its body diode. The BJT appeared and then fell into obsolescence due to the advent of IGBT at the higher end and power MOSFET at the lower end. The invention of IGBT is an important milestone in the history of power semiconductor devices. Commercial IGBTs are available with 3500 V, 1200 A, but up to 6.5 KV and 10 KV devices are under test in laboratory. Trench gate IGBT with reduced conduction drop is available up to 1200 V, 600 A **.** IGBT intelligent power modules (IPM) from a number of vendors are available for 600 V, 50-300 A and 1200 V, 50 –150 A to cover up to 150 hp ac drive applications. IGCT (also called GCT) is basically a hard-driven GTO with built-in gate driver, and the devise is available with 6000V, 6000 A (10 KV devices are under test). Recently, ABB introduced reverse blocking IGCT (6000 V, 800 A) for use in current-fed inverter drives. Large band gap power semiconductor device with silicon carbide (SiC) that has high carrier mobility, high electrical and thermal conductivities and strong radiation hardness is showing high promise for next generation power devices. These devices can be fabricated for higher voltage, higher temperature, higher frequency and lower conduction drop. SiC diodes are commercially available, and other devices are expected in future.

7. Progression of Power Converters

The traditional diode and phase-controlled thyristor converters that work on line- commutation principle are the most primitive type of converters. Thyristor-based cycloconverters have been popularly used in multi-MW ac motor drives. Phase-controlled of converters create line power quality problems due to distortion of current wave. Besides, phase control causes deterioration of line power factor. Rigorous harmonic standards have been developed to combat the line power quality problem. Static VAR compensators (SVC) and active filters, operating on PWM voltage-fed converter principle, have been developed to solve the power factor and harmonic problems, respectively. Japanese railway system recently installed 48 MVA SVC using GTO-based multi-stepped voltage-fed converter principle.

Since PWM converters can operate in both inversion and rectification modes, they can replace phase-controlled converters and cycloconverters solving the harmonics and power factor problems on the line side. Voltage-fed PWM converters have been established as industry-standard all over the world. Both sinusoidal and space vector PWM techniques are widely used, but the later has the advantages of improved PWM quality and higher undermodulation range for isolated neutral loads (such as ac motors). IGBTs are commonly used in low to medium power converters, whereas GTOs (and recently IGCTs) are used at higher power levels. Three-level converter topology, preferred in high voltage high power applications, gives better harmonic performance with same PWM frequency as in two-level inverters. An example is 10 MVA GTO three-level inverter synchronous motor drive for rolling mill which was introduced by Mitshubishi a few years ago. Current-fed converters are competetive to voltage-fed converters in many applications. High power load-commutated thyristor inverter (LCI) synchronous motor drives are very popular in industry. Double-sided PWM current-fed converters using self-controlled reverse-blocking devices (GTOs or IGCTs) have essentially the same features as those of voltage-fed converter system.

There has been an enormous growth of soft-switched converters in recent literature. The traditional voltage-fed and current-fed converters operate on hard switching principle. Soft-switched converters, operating on zero voltage or zero current (or both) switching principle, can provide the advantages of minimizing device switching loss, elimination or reduction of snubber size, improvement of device reliability, reduced dv/dt stress on machine insulation, reduced EMI problem, elimination of drive motor bearing current and possible voltage boost effect at motor terminal with long inverter-motor connecting cable (these are inherent problems in hard-switched converters). Although soft-switching converters have been popularly used in high frequency link SMPS and resonant inverters, they have hardly appeared in the market place for ac motor drives. Extra power circuit components, control complexity and possibly exaggeration of claims are the reasons for this demise. ABB has recently used LC low-pass filter at the motor terminal to solve some of the hard switching problems in IGCT-based AC1000 class of drives.

8. Progression of Machines and Drives

The evolution of electrical machine, the workhorse in a drive system, has been slow and less dramatic than those of power semiconductor devices and converter circuits. In a high performance drive, the machine constitutes a very complex element. For drive system engineers, advanced studies relating to machine modeling, control, and estimation of states and parameters (which vary widely) are the exciting R&D topics today. With the advent of low-cost variable frequency inverters with improved power semiconductor devices, advanced DSP's, powerful ASIC chips, and advanced control and estimation techniques, ac drives are progressively replacing the traditional dc drives. Both induction and synchronous machine drives have been widely used. However, cage type induction motor drive with voltage-fed inverter is the favorite in majority of industrial applications. Slip power recovery drives using wound rotor induction motor have been used in limited speed control range in multi-MW applications. Synchronous motor drive has the advantage of improved efficiency but at a higher cost. However, its life-cycle cost is generally lower. Besides, unity or leading power factor operation provides advantage for the converter. Very high power drives (such as for rolling mills and ship propulsion) use wound-field synchronous machines with cycloconverter, load-commutated inverter, or PWM multi-level inverter system. Permanent magnet (ferrite or NdFeB magnet) synchronous machines (PMSM) can generally be classified into trapezoidal and sinusoidal machines depending on the induced voltage wave at the machine terminal. Trapezoidal machine drive with the inverter, position sensors and control is defined as brushless dc motor (BLDM) because of its close analogy with the dc motor performance. PMSM drives are widely used in fiber spinning mills, servos, robotics, EV/HV and machine tools.

9. Progression of Control and Estimation

Advanced drive control and sensorless estimation techniques are fascinating and challenging research topics now-a-days. Although simple volts/Hz control has been extensively used in industry, the advent of vector or field-oriented control has brought renaissance in modern high performance control of ac drives. This type of control, in spite of complexity, is expected to be universal in future. The adaptive control methods, such self-tuning control (STC), model referencing adaptive control (MRAC), sliding mode (SM) or variable structure (VS) control can be easily applied over the vector control. Speed sensorless vector control is again a popular R&D topic. Of course, commercial drives are already available in the market with speed sensorless vector control. Speed estimation of induction motors has been proposed by slip signal synthesis, model referencing adaptive system (MRAS), speed adaptive flux observer (Luenberger observer), extended Kalman filter (EKF), slot harmonics, and injection of auxiliary signals in the machine stator. Machine parameter variation imposes a formidable difficulty in all these methods, particularly as the speed or frequency approaches zero.

A type of performance-enhanced scalar control, known as DTC (direct torque control, or direct torque and flux control), has recently received a lot of attention in the literature. With control simplicity compared to vector control and performance close to vector control, it has found applications in industry.

In recent years, AI techniques, particularly fuzzy logic (FL) and artificial neural networks (ANN), have shown high promise for application in power electronic systems. An intelligent control based on FL or ANN, can give robust performance of a nonlinear parameter varying system with load disturbance, and design of such a system may not require mathematical model. Fuzzy logic has been applied in speed control of drives, flux programming efficiency optimization control, wind generation and photovoltaic systems, slip gain tuning of vector control, machine parameter estimation, estimation of distorted waves in power electronics, diagnostics, nonlinearity compensation, and so on. ANN is a more generic form of AI, and both feedforward and recurrent (or feedback) ANNs have been used in hysteresis-band and space vector PWM controllers, feedback signal estimation of drives, model identification and adaptive drive control, multi-dimensional nonlinear look-up tables, delayless filtering, diagnostics, FFT signature analysis of waves, estimation of distorted power electronic waves, and so on.

10. Conclusion

The paper has given a brief but comprehensive review of world energy scenario, environmental pollution and safety problems of energy generation, mitigation of environmental problems with particular emphasis on extensive application of power electronics. Renewable energy sources, particularly wind and photovoltaic that heavily depend on power electronics, have been emphasized. Electric and hybrid vehicles which are also intensive with power electronics are discussed. Currently, EV and HV are uneconomical in general applications, but as the gasoline price increases, environmental quality standards are enforced, and advances of power and energy storage devices become significant, they will find customer acceptance in future. The importance of power electronics and its recent technology advances have been briefly reviewed. A time has now come when in any country's energy policy, the role of power electronics in energy generation, environmental control and energy saving of electrical apparatus should be adequately emphasized. This is particularly true for USA where energy appetite is voracious.

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References

[1] B. K. Bose, *Modern Power Electronics and AC Drives,* Prentice Hall, Upper Saddle River, 2002.
[2] S. Rahman (Ed.), Proceedings of the IEEE Special Issue on “2001: An energy odyssey”, vol. 89, December 2001.
[3] B. K. Bose, “Energy, environment and advances in power electronics”, IEEE Trans. on Power Electronics, vol. 15, pp. 688-701, July 2000.
[4] S. R. Bull, Renewable energy today and tomorrow”, Proceedings of the IEEE, vol. 89, pp. 1216-1226, August 2001.
[5] 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.
[6] J. Jaydev, “Harnessing the wind”, IEEE Spectrum, pp. 78-83, Nov. 1995.
[7] W. Sweet, “Power and energy”, IEEE Spectrum, pp. 62-67, Jan. 1999.
[8] B. K. Bose, “Recent advances and trends in power electronics and drives”, Proc. of NORpie Workshop, Helsinki, pp. 170-181, Aug. 1998.
[9] B. K. Bose, “Power electronics – a technology review”, Proc. of the IEEE, vol. 80, pp. 1301-1334, Aug. 1992.
[10] B. K. Bose (Ed.), *Power Electronics and Variable Frequency Drives*, IEEE Press, NJ, 1997.