

Power Electronics and Motion Control-Technology Status and Recent Trends

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Abstract:

Power electronics and motion control has emerged as a very important technology in the recent trend of industrial automation. The paper reviews the technology status and trends in power electronics and motion control with emphasis on ac machine drives. A comprehensive review of power semiconductor devices, converter circuits, machine drives, and various motion control techniques is included. Finally, the impact of expert systems, fuzzy logic, and neural networks in the intelligent motion control has been discussed

Introduction

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INTRODUCTION ENERGY in electrical form is the most important element in modern industrial civilization. Per capita consumption of electricity has been a key measuring stick of a nation's living prosperity. The bulk of this energy is generated in hydro, fossil fuel, and nuclear power stations. In an industrialized nation today, an increasingly significant portion of the generated electrical energy is processed through power electronics for various applications in industrial, commercial, residential, aerospace, and military environments. At one end of the spectrum, switching mode dc and ac power supplies are used in electronics, computers, and instrumentation applications. Power electronics is routinely used in electrochemical applications, such as electroplating, metal refining,

anodizing, and production of chemical gases. Incandescent lamp dimming, heating and welding control, and high-frequency fluorescent lamp ballasts are well-known. Solid-state power line conditioners are being used for harmonic filtering and static VAR compensation on utility systems. Very recently, distributed VAR generators are being proposed for flexible ac transmission systems. High-voltage dc (HVDC) transmission and asymmetrical frequency intertie systems use converters at both ends. Solid-state dc and ac circuit breakers have been used in low-to-medium power circuits. Heating, melting, and heat treatment of metal use induction heating generated by power electronics apparatus. The largest and possibly the most complex application of power electronics is in the area of electrical machine drives. The applications include computer peripheral drives, machine tool and robotic drives, pumps, blowers, textile and paper mill drives, cement mill and rolling mill drives, etc. Very recently, magnetically levitated (MAGLEV) Paper IPCSD 93-3, approved by the Industrial Drives Committee of the IEEE Industry Applications Society. This paper is based on the invited plenary presentation at the 1992 IEEE Power Electronics Specialists Conference, Toledo, Spain, June 29-July 3, and the keynote address delivered at the Conference on Industrial Drives, Rockhampton, Australia, September 18-20, 1991. Manuscript released for publication March 1, 1993. The author is with the

Department of Electrical Engineering, University of Tennessee, Knoxville, TN 37996. IEEE Log Number 92 12373. linear synchronous motor propulsion with a superconductive field coil has been used for high-speed mass transportation in a number of countries.

In all such applications, the clear trend indicates the supremacy of ac drives over dc drives, which will be eventually pushed out of the market. To satisfy our ever-increasing appetite, electrical energy has so far been generated primarily from fossil and nuclear power plants without due consideration of their environmental impact. Urban air pollution, acid rain, and the global warming effect (greenhouse effect) are mainly due to emission from fossil fuel plants, and the safety issues of nuclear power plants are now causing tremendous concern in our society. How can we continue improving our living standard without endangering our environment? One possible solution is energy conservation by widespread use of power electronics. It has been estimated that in the United States, roughly 15-20% of energy can be saved by more efficient use of electricity with the help of power electronics. There will be greater savings as power electronics becomes cheaper in the future. In the United States, approximately 20% of generated energy is consumed in lighting load, and another 60-65% is consumed in electrical machine drives. Incandescent lamps are popular but are grossly inefficient in lumens/watt rating.

Ordinary fluorescent lamps are two to three times more efficient. Again, by using a high-frequency power electronics ballast, the efficiency can be further improved. The additional advantages of the high-frequency ballast are reduced size, lamp dimming control, and soothing effects on the eye. The majority of electrical drives are used in pumps, blowers, and compressor-type applications. It has been well established that adjustable-speed drives (instead of throttle flow control with fixed-speed drives) can save considerable amounts of energy. Again, the majority of these drives operate at light load condition most of the

time. It is possible to improve efficiency that is further reduced by flux efficiency optimization control. As power electronics becomes cheaper, every machine will eventually use power electronics in the front end. The variable-frequency solid-state starter for fixed-speed application can easily provide Nola-type reduced flux efficiency-improvement control and, at the same time, maintain unity power factor on the ac line. The converter with the control can be integrally mounted on the machine frame in the lower end as the next generation converters shrink in size. The hydraulic, pneumatic, and heat engine-type drives are eventually expected to be replaced by power electronic controlled electrical drives. In an all-electric airplane, the hydraulic drives for the control surfaces can be replaced

POWER SEMICONDUCTOR DEVICES Power semiconductor devices constitute the heart of modern power electronic apparatus, and therefore, this paper would be incomplete without a discussion of the trends in these devices. The power electronics era began with the invention of the glass bulb mercury arc rectifier at the beginning of this century. However, the modern solid-state power electronics era started in the last 1950's with the invention of thyristors, which are also known as silicon-controlled rectifiers.

The advent of the thyristor revolutionizes power electronics, bringing power electronics to the marketplace on a large scale. Gradually, other types of devices, such as triacs, gate turn-off thyristor (GTO's), bipolar power transistor (BPT's or BJT's), power MOS field effect transistor (MOSFET's), insulated gate bipolar transistors (IGBT's), static induction transistors (SIT's), static induction thyristors (SITH's) and MOS-controlled thyristors (MCT's) were introduced. In parallel with new device evolution, the power rating and switching performance of the existing devices began improving dramatically. In a power electronic apparatus, the device's cost may not exceed typically 20 to 30%, but the device heavily influences cost, size, weight, and performance of the total equipment. Generally, the

evolution of power electronics has followed the evolution of devices. Again, device evolution has been heavily influenced by solid-state technology evolution brought on by microelectronics researchers.

Modern power electronics apparatus use both power devices and microchips where both are essentially digital in nature. An important trend in power electronics is that the operating frequency of high-power devices is continuously increasing, and converter topology is being modified to handle high frequency with high power in order to shrink equipment size and improve its performance. Thyristors, especially the phase-control type, have traditionally been the workhorse in power electronics. Starting originally with the C35 type (800 V, 35 A) introduced by GE, the modern light-triggered high-power thyristors (6 kV, 3.5 kA) have been evolving for more than three decades during the thyristor era. The thyristor application is common, ranging from a simple battery charger to large megawatt HVDC converters and thyristor-controlled reactor (TCR) static VAR compensators in a utility system.

The GE SCR Manual had been the Bible in power electronics for a long time. However, the S curve for R&D and applications of the device has now practically reached a saturation point. In the future trends of power electronics, this device is expected to play a diminishing role, which will be discussed later. Inverter-grade thyristors that were used in force-commutated voltage-fed inverters (e.g., McMurray inverter) have already met their technological demise. The triac or bidirectional thyristor was invented by GE almost immediately after thyristor commercialization and found tremendous popularity for light dimming and heating control-type applications.

Except for zero voltage ac line switching, the role of the triac will diminish in the future. The GTO, which is another invention of GE that appeared at almost the same time as the triac, was a glimmer of hope, but soon, its research and applications were abandoned,

considering that the device practically has no future. However, from the late 1970's and early 1980's, a number of Japanese corporations introduced high-power GTO's in the market and substantiated that voltage-fed inverters built with self-controlled GTO's have considerable efficiency, size, and reliability advantages over those with force-commutated thyristors. However, the GTO has large switching loss and shows a second breakdown problem at turnoff that demands a large turn-off snubber. The loss consideration also restricts switching frequency typically below one kHz. Recently, lossless or regenerative snubbers [46] that help to increase frequency and efficiency of GTO converters have been proposed. Today, GTO converters enjoy unique popularity in the high power range. Bipolar and field-effect transistor principles were known from the beginning of the solid-state era, but the modern power transistors and power MOSFET's penetrated the market from the mid 1970's. Darlington power-transistor modules with built-in feedback diodes (as high as 1200 V, 800 A) gradually pushed the voltage-fed transistor inverter rating up to several hundred kilowatts. Higher switching frequency (several kilohertz) and, consequently, the reduced snubber size were definite advantages over the GTO converter. Power MOSFET's also found large market acceptance, but because it is a majority carrier high-frequency high-conduction drop (especially for highvoltage rating) device, it is dominant in high-frequency lowpower applications such as switching mode power supplies and brushless dc motor (BLDM) drives.

The introduction of the IGBT in the early 1980's has brought a visible change in the trend of power electronics. The IGBT is a hybrid device that combines the advantages of the MOSFET and the bipolar transistor. The device is slightly more expensive than the power transistor, but the advantages of higher switching frequency, MOS gate drive, the absence of the second breakdown problem, snubberless operation, reduced Miller feedback effect, and the availability of

the monolithic gate driver with “smart” capability provides the overall system advantage to IGBT power converters. Because of higher switching frequency, ac drives can be designed without acoustic noise. The power rating and performance of the IGBT are continuously improving.

Undoubtedly, it is the biggest challenger the power transistor, which will eventually drive the latter out of the market. For high-frequency high-power applications, SIT has recently been introduced in Japan. In performance, it is comparable to the traditional vacuum triode tube. The reliability, noise, and radiation hardness of the SIT are claimed to be superior to the power MOSFET. The device has been used in Japan for linear applications, such as audio, VHF/KJHF, and microwave amplifiers and switching applications such as induction heating, AM/FM transmitters, high-voltage low-current power supplies, and ultrasonic generators.

The excessive conduction drop of the SIT will rule out its application in the majority of power electronic apparatus. Japan has also recently introduced the SITH, which is often called the SI-thyristor. Basically, it is a field-controlled diode (not a thyristor) and is similar to a device reported by GE in the early 1970's. Similar to the SIT, it is a normally-on device and requires reverse gate current to turn it off. Otherwise, the device has GTO-like characteristics except that the turn-off current gain is somewhat lower, and conduction drop is higher, but the switching frequency, dv/dt , and di/dt ratings are somewhat improved. The device has been used in Japan for applications such as static VAR compensators, induction heating, and high-frequency link dc/dc converters. At this point, no future impact of the SITH is visualized in power electronics. A device that is showing tremendous future promise is the MOS-controlled thyristor (MCT).

The MCT is basically a MOS-gated thyristor that can be turned on and off by a small pulse on the MOS gate. The device was announced by GE in November 1988, when sample devices (50 A, 500 V/1000 V and 100 A, 500

V/100 V) were distributed. Then, Harris Semiconductor commercially introduced the device (600 V, 75 A) in 1992. An MCT is comparable to the IGBT in switching frequency, but its lower conduction drop is a definite advantage. However, SOA of MCT is somewhat limited and requires a snubber. Considering that it is a new device and there is future evolutionary improvement potential, MCT's are expected to have a significant impact in medium- to high-power electronics. Although silicon has been the basic raw material for power semiconductors and microelectronics, several other raw materials, such as gallium arsenide, silicon carbide, and diamond (artificial in thin-film form) are showing tremendous future promise. These materials are difficult to process but provide the capability for high-frequency, high-voltage, high temperature, and low conduction drop [28]. Undoubtedly, the power MOSFET does not have any competitor on the horizon.

The future of the thyristor is bleak, considering the trend of deemphasis of phase control applications, which will be discussed later. The future of the SITH and the BJT is bleak, as was discussed before. Once full-blown MCT's are commercially available in the market, they will provide stiff competition with IGBT's. Considering the success potential of the high-power MCT, it will be a competitor with the GTO in the future. Note that high-frequency power devices are characteristically asymmetric blocking. Of course, both the IGBT and the MCT can be designed to be reverse blocking (with sacrifice of switching speed), or a series diode can be added with a normal device (causing large conduction drop, i.e., higher loss).

POWER CONVERTERS

Thyristor converters with phase control and line commutation have been used from the beginning of modern power electronics era. The topology of the thyristor converter is simple: It has high efficiency (with negligible switching loss), and its simplicity of control have made this class of converters popular in myriads of applications. However, the disadvantages are that

phase control generates lower order harmonics in line and load, and demands lagging reactive current from the line. With growing phase control applications, utility systems are facing serious power quality problems. Recently proposed Standards IEEE 519 and IEC 555 tend to severely restrict harmonic injection into the power line by this type of nonlinear load. Bulky and expensive passive filters have been used to combat the harmonic problem.

Static VAR compensators in the form of thyristor-controlled reactors (TCR's) in conjunction with thyristor-switched capacitors (TSC's) and harmonic rejection resonant filters have been used. More recently, PWM-type active power line conditioners (APLC's) that can compensate harmonics as well as reactive power are appearing on the horizon. However, excessive cost and complexity of such schemes will tend to deemphasize phase-controlled converter applications in the future. On the other hand, line-side converters using the PWM technique (which will be discussed later) that have a built-in solution to the above problems will be increasingly emphasized.

The dc-link power conversion system is by far the most popular configuration for industrial applications. This topology can be classified as voltage-fed and current-fed types. The voltage-fed PWM inverters have found common acceptance in industry because high-frequency power devices have asymmetrical blocking characteristics. A popular topology, especially for ac drives applications, is the PWM inverter with the diode rectifier in the front end. One problem with the diode rectifier is that the line current distortion factor is poor with the capacitor filter in the dc link. Besides, the circuit does not have line power feedback capability. The harmonic problem can be solved with the boost chopper in the dc link [37], [38] that controls the dc link voltage and shapes the line current to be sinusoidal. In fact, buck-boost choppers have also been proposed so that the dc voltage can be regulated to any value Wl . An elegant solution to the voltage-fed conversion scheme

is to use a dual or double PWM converter. Although such a converter system is expensive and the control is complex, the scheme is ideal for four-quadrant application.

The lineside PWM converter will act as a rectifier in the forward power flow but as an inverter in the reverse power flow. The line side counter emf can be controlled in magnitude and phase to obtain sine wave line current at unity power factor. With partial or no-load operation of the line-side converter, auxiliary VAR (leading or lagging) and harmonic compensation can be provided to the utility system. In fact, with the load-side converter and the load disconnected, the circuit can act as the APLC, as mentioned previously. With the decreasing trend of converter cost, this type of topology will find increasing acceptance. Recently, a multimegawatt double PWM converter of this type has been introduced [40] for rolling mill application, replacing the conventional cycloconverter drive. For ac electric locomotives, double PWM

topology has been used; however, the front-end converter is the single-phase type. The electrolytic capacitor is the weakest link in a voltage-fed converter system. Of course, it can be replaced by a more reliable ac capacitor with a size and cost penalty. If the converter PWM frequency is high (using the IGBT or power MOSFET), with some control sophistication, the size of ac capacitor can be substantially reduced [29]. Very recently, elimination of the electrolytic capacitor by a high-frequency active filter has been proposed. Current-fed converters are competitors to voltage-fed converters. A popular topology of this type is the forcecommutated ASCI inverter with a front-end thyristorphasecontrolled rectifier. If the load is a synchronous machine type that can operate with leading power factor load, the ASCI inverter can be replaced by a load-commutated phasecontrolled inverter. With current-fed topology, the control and regeneration features are simple, but load and line side harmonics, pulsating torque, poor line displacement

factor, and bulky dc link inductance are problems. Double PWM [14] or single PWM (with phase control in the front end) current-fed converters using self-controlled reverse blocking GTO's have found acceptance in multimegawatt ac drives. A double PWM converter is more expensive and has control complexity but solves the harmonics and power factor problems, as mentioned previously. The topology needs an ac capacitor bank both on the line and load sides to provide PWM harmonic filtering and bypassing of the inductive load current. Again, like the double PWM voltage-fed converter, the line power factor can be programmable (unity, leading, or lagging), and the lineside converter alone (with dc link inductance) can function as the APLC. Considering all these features, it appears that the voltage-fed topology will invariably win in the competition. A class of direct frequency changer (cycloconverter) operating on PWM principle has been forwarded from the beginning of 1980's that is also known as a matrix or Venturini converter [161].

The converter can directly generate a variable-frequency variable-voltage wave for an ac motor drive with the line side power factor as unity (or programmable), but the lack of availability of ac switches with low loss, high frequency, and a bulky line side capacitor bank make the scheme somewhat unattractive. Thus far, discussion has been centered on converters that use a hard or stressed switching method. Recently, resonant link topologies that permit zero voltage or zero current switching (soft switching) have been proposed, practically eliminating the switching loss. This class of converters is already very popular in switching mode power supplies.

In a dc resonant link topology [12], [13], the rectifier dc voltage is converted to high-frequency pulsating dc with the help of a resonant circuit. The zero crossing voltage pulses are then used to synthesize variable-frequency variable-voltage waves for motor drives. Besides high converter efficiency, the added benefits are absence of snubbers, lower heatsink size (due to reduced losses),

higher device reliability, elimination of machine magnetic noise, low EM1 problem, and longer machine insulation life (due to lower dv/dt). The double resonant link PWM converter with the above benefits can be [301. easily built [41].

There is, however, a penalty of a higher device voltage rating and a slightly increased harmonic current in the load. Recently, a quasi-resonant link converter scheme has been proposed to combat the harmonic problem [42]. Considering the advantages, resonant link converters show high promise for the future. It is expected that eventually, all types of converters (ac-dc, dc-ac, ac-dc-ac) will accept this principle. At present, considerable amounts of research and development are in progress in this area. The concept of the ac resonant link power conversion was known in the early 1970's [22]. In a typical scheme, three-phase ac is converted to high-frequency ac (several kilohertz) by the phase-controlled cycloconverter and is then cycloconverted back to variable-frequency ac for the motor drive. The link frequency is maintained constant by a parallel resonant circuit. Such a scheme can have bidirectional power flow, and the input displacement factor can be maintained as unity, leading, or lagging.

Recently, the ac resonant link converter has been proposed [21] using self-controlled ac switches. A six-switch matrix type converter replaces the phase-controlled cycloconverter both at the input and output, and the link frequency can be raised typically to 20 kHz. Both the converter components can switch at zero voltage, giving advantage of higher efficiency. Again, the lack of availability of efficient high-frequency ac switches is the disadvantage of this scheme. Besides, the control of instantaneous power balance between the input and output to maintain the constant tank voltage is a problem. A somewhat dual form of this converter is the series-resonant double cycloconverter [3 11, which normally uses anti-parallel thyristors as ac switches. The thyristors are commutated at zero current due to discrete current pulses in the ac link.

AC MACHINE DRIVES

An electrical machine is the workhorse in a drive system, and understanding its characteristics in detail is of crucial importance for a modern high-performance drive. Machines have been with us for more than a century, and throughout this period, extensive studies have been made on them. Even the recent IEEE conferences including a conference exclusively devoted to machines (the International Conference on Electrical Machines (ICEM)) generate large numbers of publications in this area. The evolution of machine technology, unlike that of power devices, converters, and control, has been long and slow and hardly showed any dramatic invention. The primitive dc and ac machines were bulky, expensive, and had poor performance. Better understanding of machine characteristics coupled with extensive theoretical studies and availability of new materials resulted in the improvement in the machine's design. The advent of modern digital computers and finite element techniques have helped machine analysis and design optimization. Recently, high-energy magnets, low loss amorphous metal, and high-temperature superconductivity are showing much promise. Studies on machine performance with converter interaction, dynamic modeling, control, estimation, measurements, and simulation techniques have received tremendous impetus for high-performance drive systems. It is no wonder that so many traditional machine, power, and control system engineers today are switching to the power electronics area

AC or "brushless" machines can be categorized as induction machines, synchronous machines, and switched reluctance machines. Induction machines, particularly the cage type, have been the traditional workhorse for fixed and variable-speed drives (excluding the dc drives) because of simplicity, economy, ruggedness, and reasonably high efficiency. Synchronous machine drives are close competitors to induction motor drives. Between the permanent

magnet and wound-field synchronous machines, the latter is popular in multimewatt drive applications (especially in pumps and blowers) because of simplicity of converter configuration. However, induction motor drives with self-commutated converters have recently been favored in such applications. Wound-field machines with superconductive cooling of the field coil are showing renewed promise due to the prospect of high-temperature superconductivity. Linear synchronous machines (LSM's) with cryogenic field cooling have been seriously considered for high-speed MAGLEV transportation. For example, Japan is now building such a transportation system between Tokyo and Osaka that will run at 300 mi/hr. The excitation system in this drive will be carriage mounted, whereas the track will contain the segmented stator winding that will be fed by a 50 MW GTO voltage-fed inverter [32]. Recently, permanent magnet synchronous machines have given stiff competition to induction motor drives in the low to medium power range. This class of machines has two categories: the conventional surface magnet type and the more recent buried or interior magnet type. Surface magnet machines again have two classes: trapezoidal and sinusoidal. The former type, with position sensor and self-controlled converter, perform the commutator function and is traditionally defined as brushless dc motor (BLDM). A PM machine is generally more expensive than an induction machine but has higher efficiency and reduced size with a high-energy magnet. We are expected to see a close race between PM and induction motor drives in the future, when a high-energy permanent magnet becomes available at an economical price. Switched reluctance machines (SRM's), which are a class of variable reluctance motors (VRM's), have been known for over a century, but recently, interest has been revived in their application. The stepper motors, which is a close relative of the SRM, is popular in incremental-type motion control of computer peripheral drives but are not generally considered for industrial drives because of poor performance. The SRM has a concentrated stator

winding, but there is no magnet or winding on the rotor. The machine is simple and economical, but an absolute position sensor is mandatory. The pulsating torque and acoustic noise are serious problems in this machine. Of course, various position-estimation and pulsating-torque elimination methods have been attempted recently. A converter is indispensable in the SRM drive (unlike other types of machine), and multiple machine operation with a single converter is not possible. Developmental SRM drives have been used in specialized applications, and their commercialization has been attempted seriously, but it is doubtful whether they will ever compete with induction motors in general industrial applications

CONCLUSION

The paper gives a comprehensive technology status review as well as recent trends of power semiconductor devices, various converter topologies, ac machine drives, and advanced machine control techniques. Emphasis is given to the induction motor drive, which is the principal workhorse in industry. Expert systems, fuzzy logic, and neural networks are the emerging technologies that have large potential impact on power electronics. In the beginning, the role of power electronics for energy saving and environmental pollution was highlighted. In conclusion, it must be mentioned that by now, power electronics has established itself as a strong technological discipline that will seriously influence industrial development and economic competitiveness of nations in the near future. With the recent political trends around the globe, it appears that economic competitiveness will be the key to a nation's survival and prosperity. In highly automated industrial environments in the future, computers, power electronics, and motion control will possibly emerge as the most important technologies. In spite of tremendous technology development in power electronics, there seems to be a large gap in its industrial applications. Unfortunately, the technology is somewhat invisible to the public eye, and therefore, its

full benefit potential has not yet been tapped. It must be emphasized that we, the community of power electronics engineers, have the responsibility to educate the public and promote its importance and visibility around the globe so that the technology is utilized to the full benefit of our society. This will also enhance the dignity and prestige of our profession.

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