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SCIENCE

Semiconductor Alternating-Current Motor Drives and Energy Conservation

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The recently announced technology of semiconductor alternating-current motor control conserves energy by increasing the system efficiency of electric motor drives used in variable-rate industrial processes. The announcement has occasioned much comment and interest since the technology involved is generically related to systems well known in the trade. Its development represents the application of available and emerging techniques in an area where there is a clear-cut opportunity for improving industrial energy usage. The interplay of changing economics, ingenious engineering, and marketing demands is particularly strong and illustrates the multiple hurdles to be overcome before new ways of performing old functions in a commercial context can be achieved.

Summary. The concentration of electrical energy usage in alternating-current motor drives presents an opportunity for substantial conservation. Emerging advances in power semiconductor transistor systems will support a major commerical effort to this end. An alternating-current synthesizer for this purpose may soon be available. The synthesizer produces electricial power of variable and programmable frequency, voltage, and wave form so that performance can be optimized. This technology provides the additional opportunity for fundamental improvements in electrical distribution and usage systems in the longer term. Power processing with semiconductor a-c motor controls is expected to become widespread in the near future.

However, there is another aspect of importance. Not only so-called breakthroughs but also incremental improvements in technology, accumulated over time, can alter the basic character of an industry or an activity. Looking forward, the prospects for major beneficial changes in electrical usage are indeed profound if this embryonic technology is followed through to its logical conclusion. It goes much further than merely motor drives. Of course, there is no guarantee that such a revolution will occur even over a long period, but the possibility is there. It is our purpose in this article to describe the opportunity, our response to it, and our thoughts about its eventual impact.

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The Opportunity

In 1976, an Arthur D. Little (*1*) report for the Federal Energy Administration produced what was for some a surprising analysis of the consumption of electricity by electric motors in the United States. This analysis indicated that motors account for nearly two-thirds of total U.S. electricity consumption. Heating, lighting, and all other applications, while more conspicuous, nevertheless account only for the remaining third. Furthermore, more than 40 percent of the electricity used to drive electric motors is consumed solely by industrial motor drives, excluding heating, ventilating, and air-conditioning (HVAC) applications. Industrial motor usage thus accounts for 27 percent of all electrical energy consumed in the United States. This consumption is primarily spread over roughly 20 million integral horsepower motors, 90 percent of which fall within the size range 1 to 200 horsepower. These motors are used principally to drive pumps, compressors, fans, and blowers in the process industries, such as the chemical, petroleum refining, pulp and paper, primary metals, and food and beverage industries. These facts of electricity usage have helped isolate one of the major opportunities for saving energy nationally (see Fig. 1).

National Need for Variable-Speed Motor Operation

To understand the implications for energy savings, we first note that when variable-speed control of an integral horsepower motor is required, the traditional approach has been to use a direct-current motor. Because it needs only simple voltage regulation to vary its speed, the d-c electric motor controller is relatively inexpensive compared to other types of speed controls. The d-c motor itself, however, is bulky, expensive, and not amenable to many industrial environments. On the other hand, the squirrel-cage induction motor is the industry workhorse because it is the simplest, cheapest, and most reliable of the various types of integral horsepower motors that are available. These operational advantages have led to its extensive utilization (*2*).

The nominal speed of an a-c induction motor is fixed by the number of poles in the motor and the frequency (f) of the electricity applied to it (nominal revolutions per minute = $60f$ divided by the number of pole pairs). Almost invariably, the frequency of electricity in the United States is 60 hertz, and thus the standard two-pole motor runs at about 3600 rev/min. Unfortunately, a constant-speed motor is not well suited to the majority of process applications, in which variable throughput is required. The common solution to this problem is to apply mechanical throttling while con-

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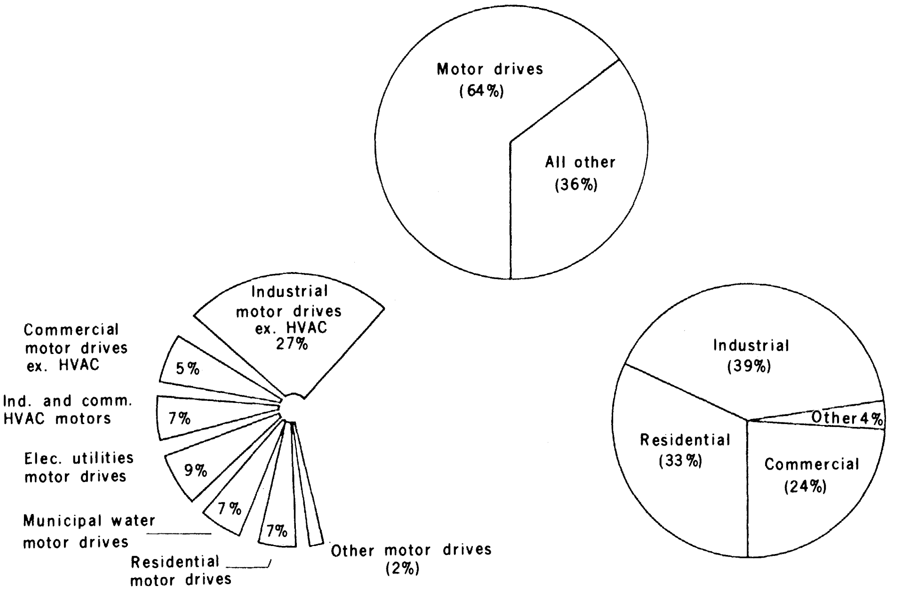

Fig. 1. Electric energy consumption in the United States.

tinuing to operate the motor at nominal speed. An example is the use of a control valve in liquid pumping systems. In such an installation, a motor-driven pump runs at full speed, while the position of a valve within a pipe is altered to achieve desired flow rates up to the maximum. Such systems are widespread in industry and generally operate with high reliability, but they are energy-inefficient in applications where the throughput is substantially less than 100 percent of the maximum (*3*). For example, to achieve a throughput of 40 percent of the rated maximum, it is necessary to consume 70 percent as much electrical energy as required to operate at full throughput, while dissipating 30 percent of the electrical energy as heat across the control valve. Since energy costs historically have been low in this country, such installations are commonplace despite their obvious waste.

The Arthur D. Little study estimated that two-thirds of all industrial motor drives are used to operate pumps, compressors, fans, and blowers. These installations typically involve the use of valves, baffles, or other types of throttling systems, and practically all of them involve a-c electric motors.

Variable-Speed Drives

An alternative to throttling is the use of an a-c variable-speed drive (VSD) (*4–6*). A VSD takes 60-Hz power and converts it, through various steps, to electricity of another frequency and voltage level. By varying the voltage and frequency simultaneously (that is, maintaining a constant voltage-to-frequency ratio), it is possible to efficiently modulate a standard induction motor. Although the VSD is itself a consumer of energy, it allows a motor-driven process to be controlled by reducing the energy input to the motor rather than by dissipating the unwanted portion of the motor's output. This is an important factor in energy consumption; the energy consumed by a motor driving a pump and operating at 70 percent frequency (and therefore at about 70 percent speed) will be only about 50 percent of the energy consumed when the motor runs at full output (see Fig. 2). Thus VSD's are an important tool for reducing industrial energy consumption. In many applications, energy savings of 50 percent or more can be achieved.

The energy savings with variable-speed motor drives are even more striking when considered in terms of primary fuel. Because approximately three units of input energy are required by an electricity generating plant to produce one unit of energy for ultimate consumption, any electricity saving has a three-for-one impact on primary fuel consumption. The potential of electronic VSD's for energy savings nationally is therefore significant.

The heart of the electronic a-c VSD is a power inverter that synthesizes the variable-voltage variable-frequency power required to obtain efficient variable speeds in a-c motors. Inverters operate by changing incoming 60-Hz utility power through a process of power switching, which yields a multistep square-wave approximation of the normally smooth sinusoidal a-c wave form. Smooth wave forms are required to avoid high heating losses in the motors. Inverters produce output wave forms whose quality depends on their cost and design features.

The slow introduction of VSD's to control a-c induction motors reflects three important user concerns—price, efficiency, and reliability. Traditionally, electronic VSD's have relied heavily on the use of silicon-controlled rectifiers (SCR's) to perform the power switching function. Because of the complex timing and control circuitry required to ensure proper on-and-off switching of SCR's, it has not been possible to keep the cost of producing these devices as low as desired. Furthermore, the poor quality of the wave forms has led to increased motor losses.

These SCR-based VSD's have been expensive devices, far more costly than the motors they have been designed to drive. Typically, they have sold in the range \$150 to \$1000 per horsepower. These high initial costs, coupled with energy efficiencies below 80 percent and reliability and maintainability problems, have limited market penetration. Nevertheless, for applications where electronic speed control of a motor was required, no other choice existed.

Advances in Semiconductor Electronics Lead to a New Generation of Inverters

The rapid advances that have been made in semiconductor electronics, particularly in power transistors, microprocessors, and integrated logic, are leading to a new generation of power inverters. These inverters offer improved wave form quality, better energy efficiency, smaller size, and improved reliability. The combination of power transistor technology and microprocessor control therefore provides an extraordinary opportunity for energy saving at a cost that makes it economically attractive.

Although some partly transistorized VSD's are already on the market, none have been offered at a price that justified broad energy conservation applications. However, the fully transistorized a-c synthesizer (ACS) is expected to be cheap enough to allow such broad use. Its key cost advantage is the elimination of iron components, such as inductors and transformers, and of large capacitors. The result is a substantial reduction in the size, weight, and cost of the equipment and an increase in efficiency from the 60 to 90 percent range to the 94 to 97 percent range and possibly higher. A comparison of the output wave form produced by a transistorized ACS unit developed by Exxon engineers with those typical of the presently available "six-step" and pulse-width-modulated units is shown in Fig. 3.

In a conventional power inverter the large, bulky, and costly output transformer, inductors, and capacitors are utilized to obtain acceptable wave form quality. A choppy wave form has a large high-frequency power component which, if used to drive the motor directly, causes motor heating, mechanical stress, and vibration. The function of inductors and capacitors is to reduce the high-frequency component. Output transformers are also used in conventional power inverters because the a-c wave form is normally produced at a low voltage level. This low voltage then requires multiplication, through use of the transformer, to match the output requirements.

In an ACS inverter all of these inductive and capacitive elements are eliminated. By use of state-of-the-art power transistors it is possible to produce directly the desired output wave form at the correct voltage. Thus the inductors, capacitors, and output transformers are not required. The necessary precise control of the switching depends on microprocessor controls.

The replacement of iron and capacitive components by semiconductor and digital controls is economically beneficial since those traditional components have been escalating in cost at about 8 percent annually, while costs of semiconductors and digital controls have been dramatically decreasing. The estimated manufacturing costs of ACS systems in volume production are currrently $10 to $50 per kilowatt, depending on size. This is a factor of 2 to 5 less than the cost of systems that are commercially available at present.

The ACS technology offers the potential for continued reductions in size, weight, and cost of VSD's. Further increases in synthesizer efficiency are feasible, which means that less energy will be dissipated as heat, so heat sinks and other metallic structures can be reduced in size or eliminated. Such possibilities will become apparent to manufacturers. These improvements, in an environment of increasingly costly energy, can lead to the widespread utilization of ACS technology in industry.

Field Results

To test ACS designs, two prototype ACS units have been installed in Exxon refineries. Both units drive pumps which, like many other refinery systems,

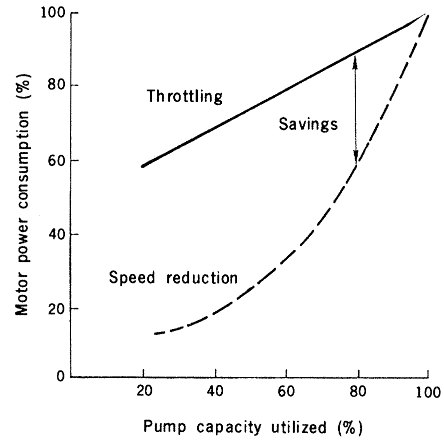

Fig. 2. Electric power consumption for pumping (relative to design conditions).

operate under variable-throughput conditions. Before the installation of variable-speed control, the throughputs of these pumps were throttled by valves while the pumps ran continuously at full speed. In our tests, the valves have been blocked in their fully open position and

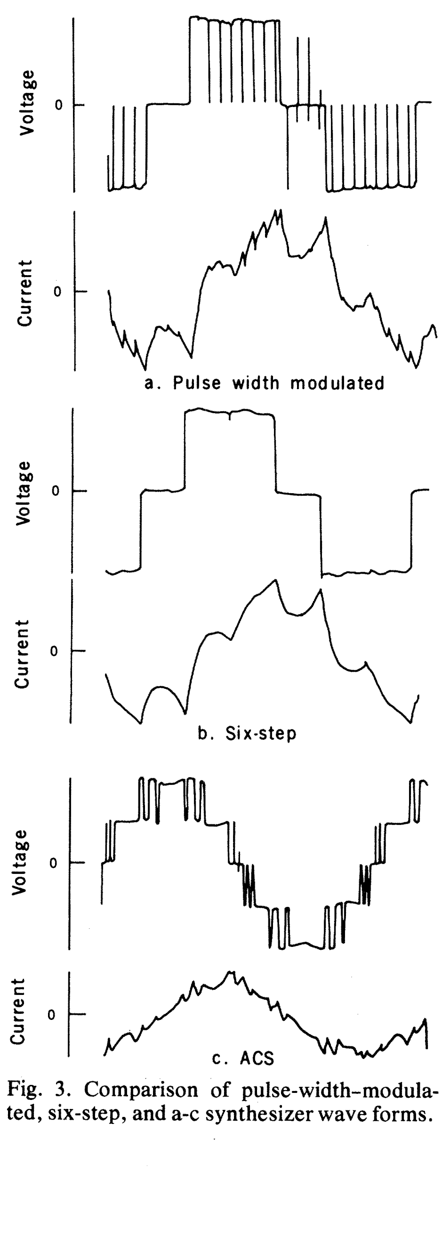

Fig. 3. Comparison of pulse-width-modulated, six-step, and a-c synthesizer wave forms.

flow control is obtained by varying motor pump speed with an ACS. The test data show that the average energy savings with ACS control and normal operating conditions have been 27 and 38 percent over a 2-month test period.

We estimate that as much as half the a-c motor power usage could be economically affected by use of VSD controls by 1990. For the motors involved, it is estimated that an average energy savings of 30 percent is realizable. Under such conditions total electricity savings would be about 110 billion kilowatt-hours, or 600,000 barrels of oil equivalent per day in terms of primary energy.

In addition, energy could be saved by applying ACS-like devices to certain nonindustrial motors such as the fans, blowers, and hermetic compressor motors used in all types of HVAC equipment, particularly air-conditioners and heat pumps. If ACS-like devices were used to control 30 percent of the motors used in such installations by 1990, with average energy savings of 20 percent, additional primary energy savings equivalent to almost 400,000 thousand barrels of oil per day could be obtained (*7*). Thus, energy savings from widespread introduction of ACS devices might exceed the equivalent of 1 million barrels of oil per day. Of course, this is a potential only, but it illustrates the leverage of new technology.

Saving More Than Energy

There are at least two additional cost savings that can be realized with ACS technology. First, when a throttled motor drive is replaced with an electronic VSD, the throttling equipment itself is not required. Thus, in a refinery many control valves and the associated control equipment can be eliminated, saving not only the initial capital cost but also the costs associated with periodic maintenance and replacement. Second, the load imposed on the motor drive system itself will be substantially reduced, resulting in extension of the normal lifetime of motors, pumps, and related equipment. In a new industrial installation, the use of ACS can result not only in ongoing savings in operating expenses but also in a lower capital cost for the plant.

Revolutionizing a-c Power

All of these advantages of ACS represent a mere beginning. Given an inexpensive and reliable device for locally converting a-c power to any desired frequency, one can envision the use of higher frequencies from which massive economies could be realized. Readily available variable-frequency a-c power would free our society from the limitations imposed by confinement to 60-Hz power. A prime example is the possibility of replacing the standard 60-Hz motor with one capable of operating at 100, 500, or perhaps 1000 Hz or more. At these higher frequencies, an electric motor is physically much smaller than a 60-Hz motor of comparable horsepower rating. The output horsepower of a motor is proportional to the product of speed and torque. Holding torque constant, the horsepower increases with higher-frequency (and therefore high-speed) operation. At present, high-frequency motors are used only for special-purpose applications, such as in aircraft, where there is a clear incentive to minimize both size and weight. A 25-horsepower, 400-Hz motor weighs roughly 30 pounds, whereas the 25-horsepower counterpart at 60 Hz weighs nearly 500 pounds. With ACS technology, it will ultimately be possible to replace large industrial motor installations with comparatively small but equally effective high-frequency units. The costs of producing, installing, maintaining, and replacing such motors will be dramatically lower than today's costs. The same arguments apply to driven equipment such as pumps and compressors.

Tomorrow's Opportunities

Other applications of ACS technology are yet to be explored. The same technology used to produce an ACS variable-speed device might also be used to produce power processing units of other types, including power converters and inverters for use on electric utility power transmission networks. Such devices might lower the cost of integrating high-voltage d-c systems into a-c networks and allow the many technical advantages of d-c power transmission to be more fully exploited (*8*). Other device applications might increase power transmission system reliability, lower network operating costs, and reduce land usage for transmission line rights-of-way.

Future applications could also include systems for integrating the power outputs from solar photovoltaic panels, fuel cells, windmills, and battery systems into conventional power networks. We therefore expect that power processing by semiconductor devices will be a technology of major, broad significance in the not-too-distant future.

References and Notes

1. Arthur D. Little, Inc., *Energy Efficiency and Electric Motors* (Publication PB-259 129, National Technical Information Service, Springfield, Va., 1976).
2. Industrial motor usage is reviewed in *Integral Horsepower Motors and Associated Controls* (Frost & Sullivan, Inc., New York, 1978).
3. R. L. Jacschke, *Controlling Power Transmission Systems* (Penton/IPC, Cleveland, 1978).
4. H. W. Weiss, paper presented at the 19th Annual Petroleum and Chemical Industry Conference, New York, 1972.
5. J. Guyeska, paper presented at the 22nd Annual Petroleum and Chemical Industry Conference, New York, 1975.
6. J. G. Anderson, *Variable Frequency Inverter for AC Drives* (Technical Association of the Pulp and Paper Industry, Atlanta, Ga., 1977).
7. Based on internal forecasts by Exxon Company USA.
8. N. Hingorani, *EPRI (Electr. Power Res. Inst.) J.* **3**, 6 (June 1978).

9. The authors wish to acknowledge Richard H. Baker's conceptualization efforts and inventiveness originally at the Massachusetts Institute of Technology in developing the alternating-current synthesizer technology now being pursued by Exxon Corporation. We also wish to acknowledge the project development leadership provided by R. L. Ricci, venture manager of the ACS group, and the assistance provided in preparing this article by T. J. Fossland, L. H. Levenberg, and especially T. P. Schiano of the ACS planning group.

Effect of Cosmic Rays on Computer Memories

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Almost everyone who has had extended experience with electronic computers has witnessed unexplained events in which a single digit of a number appears to change spontaneously, or perhaps the computer itself suddenly stops, and no way can be found for it to repeat the failure. Within the computer industry these problems are known as "soft fails," which differentiates them from the "hard fail" of a bad electronic circuit that must be replaced. A soft fail in a computer memory may be defined as the spontaneous flipping of a single binary bit, which when later tested will prove to be operating correctly.

The appearance of soft fails in computers has recently become prominent because of the α-particle problem (*1–3*). This problem was suddenly recognized in 1978 after a new generation of electronics with very small circuit components was introduced. Alpha particles (helium nuclei) are the decay particles of radioactive chains of atoms which start with uranium or thorium atoms and have emission energies between 5 and 10 million electron volts. They are produced by traces of uranium or thorium in or near the electronic circuits. These α-particles can produce up to 3 million electron-hole pairs (but not more) within the silicon crystal on which the electronic circuits are fabricated. Until 1978 electronic components in computers were apparently not sensitive to noise bursts of 3 million electrons, so the problem was not recognized earlier.

To understand the magnitude of the problem, one must realize the incredible reliability of electronic circuits and the almost immeasurably small amounts of uranium or thorium that can cause problems. Typically, engineers define integrated circuit reliability in units of chip fails per million hours, with nominal reliability rates of one fail per megahour. Note that this is chip fails, not individual component fails, and a chip may contain 64,000 bits of memory. This means that the mean time-to-fail of each bit on the chip is 7,500,000 years. However, in a large computer there may be 1000 such chips, which means that a soft fail might occur once very 1000 hours ($\simeq$ 6 weeks).

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