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Power Supplies

Magnetek's technology and strategy are positioned to ride the digital power supply wave

The most familiar things in electrical life run directly from the grid: lamps, stoves, and the simplest electric motors. But every device that includes digital logic, every advanced electric motor, laser, and solid-state light bulb, requires an intervening "power supply" that converts 110 V 60 Hz grid power into some different form at the doorstep of the device. On mobile or other off-grid platforms with on-board electric generators of their own, the power supply provides the interface between the local grid and the load.

Power supplies also provide interfaces between grids. A personal computer, for example, has a first power supply to interface between the 110 V AC wall socket and the 12 V DC local grid that feeds the individual cards and circuit boards. Each board is a grid in its own right, and may require a power supply of its own to provide power to different chips that run at different DC voltages. On router boards (and soon PCs) a DC-DC "brick" serves as an intermediate high-performance power supply bridging the motherboard's 12 or 24 V DC power to the 1.3 V DC Pentium-class chips and to other chips and devices (drives, displays, and so forth) that run at different voltages. Similar tiers of grids and power supplies are found on satellites, jets, tanks, trucks, passenger cars, telephone company central offices, and wireless base stations. Motor "drives" and "controllers" are special-purpose power supplies whose output can be controlled in real time by software or a human operator. Power supplies, thus broadly defined, currently constitute about a $50B global market, though the market is so highly fragmented that it's hard to pin down solid numbers.

For many decades, manufacturers of motors, test instruments, TVs, and other electrical equipment built their own power supplies in-house. Over the years, however, independent vendors emerged and took over much of the civilian market for power supplies. These vendors created large catalogs of power supplies, and sold them off the shelf, on a take it or leave it basis. Manufacturers of stereos, televisions, microwave ovens, and specialty industrial tools were content to buy this way; the electrical devices they were building didn't require anything better.

The high end of the power-supply market looked quite different. For the most part, computer and telecom manufacturers, and the manufacturers of electrical hardware for the military, built their own power supplies. Large telco central offices, for example, are built around endless racks and cabinets densely packed with hardware that requires large quantities of 48 V DC power. Alongside the first-generation manufacturers of mainframe computers, phone companies pioneered the wide-scale civilian deployment of high-power electronic equipment. And until very recently, all the major manufacturers of DC power plants for central offices and wireless infrastructure were telecom companies—Lucent, Nortel, Ericsson, and Marconi.

Then, quite abruptly, that changed. In the last four years Nortel and Ericsson sold their power operations to Emerson, and Lucent sold its to Tyco. Siemens, Germany's main vendor of telecom equipment, is out of the business too—it buys what used to be Ericsson's power supplies from Emerson. Only Alcatel (France) and Marconi are still trying to run their own shops. (Marconi's affiliate is RelTec, a Columbus, Ohio, DC power plant firm that Marconi acquired in 1999.)

The future of telecom equipment power plants now belongs to a cluster of large independents that sell to all equipment vendors. Outside the hermetic world of the old telecom-equipment vendors, Emerson was the first major player to grasp the broader importance of the DC power plant.

Power-One emerged as another significant player in the DC space (*Cisco of the Powercosm?,* May 2000). Tyco's acquisition of Lucent's unit perhaps made sense for Lucent, though it's hard to see where the natural fit is with Tyco. Other smaller independents include Peco II and Transistor Devices.

The same forces that reshaped the manufacture of power supplies for data and telecom customers are now sweeping across other segments of industrial and commercial power-supply markets. Magnetek (MAG) was one of the first vendors to grasp this. In 1991, the company acquired Plessey, Europe's leading independent manufacturer of digital power supplies for computers, and that created the nucleus of what is now Magnetek's sole business.

Power supplies for high-end data processing and telecom systems still account for one important segment of that business, with IBM generating 13 percent of the company's revenue in 2001. But Magnetek's power supplies also land in equipment used in medical diagnostics, digital imaging, and high-tech manufacturing, such as the control logic and laser light sources in semiconductor chip-slicing machinery. Its power blocks and drive systems land in cranes, mining machines, and elevators. It also manufactures "smart power modules" that can significantly cut electric power consumed by washing machines, refrigerators, and heating, cooling and ventilating units.

Though Magnetek sells hundreds of nominally different power supplies, it builds them all around a much smaller number of core engines. Its power supplies cover all possible combinations of AC-DC power conversion over output powers ranging from 3 W to 25 kW, and voltage levels from under 1 volt to over 15 kV. It designs advanced circuit topologies for high-power conversion efficiency, high-power density, and high reliability. It integrates microcontrollers, DSPs, and application-specific software algorithms to control, monitor, and communicate with external devices. It has developed wireline and wireless monitoring and control systems for telephone networks and electric utilities. It also develops systems software to manage multiple subsystems and provide an intelligent user interface.

This strategy has exceptional promise, because it is tailored to powerful trends in the underlying technology.

"Switched Mode" Power

The reinvention of the power supply is being impelled by rapid advances in fast, high-power, solid-state switches, matched by comparable improvements in capacitors, power sensors, and programmable digital logic. Switches provide the core logic by which power is converted from one voltage-current profile to another. Capacitors provide the local caches that are essential in rebuilding the power profile. Sensors allow the power supply to respond on the fly to changes in power profiles upstream and down, and to the internal dynamics of the power supply, the health of capacitors prominent among them. Digital logic and software provide the overarching intelligence and control, analyzing sensor input, reacting to transients in supply or load, or even anticipating them, and fine-tuning the power supply as the performance of its individual components changes.

Embedded lines of software code provide the simplest measure of how fundamentally power supplies have changed. Until about 1990, few power supplies contained any code at all. Today, Magnetek routinely packs 10,000-plus lines into the software and firmware in its units. And the total is rising geometrically, year by year.

Until the transistor was invented, power supplies were analog devices. These "linear" power supplies consisted of a carefully crafted, interlocking pair of precisely tuned circuits: the first matched to the character of the upstream power, the second matched to the downstream load. These circuits weren't easy to design, but they were relatively easy to build. They were inherently inefficient—the basic strategy was to draw a lot more power in than was delivered out, and to selectively dissipate power to rebuild the power profile. They relied on very bulky transformers, large filter capacitors, and large heat sinks. The only way to improve efficiency and reduce size was to use a power supply designed for a specific, narrow range of input voltage and downstream load.

Mainly for that reason, power supplies and their manufacturers proliferated. Companies that manufactured anything sophisticated enough to require its own power supply—anything from a fighter jet to a microwave oven—either built their own power supplies or bought from outside vendors that custom designed units for their specific uses.

In principle, however, a power supply need not dissipate any power at all. Unlike a thermal engine, which transforms low-grade heat into high-grade

Authors	Peter W. Huber Mark P. Mills
Publisher	Debi Kennedy
Managing Editor	Marie Lavinio
Designer	Julie Ward
Subscriber Services	Laura Parsons
Chairman	George Gilder

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motion and must always dump some heat in the process, a power supply transforms electricity into electricity. This can, in theory, be done without any loss, if the device's internal logic, sensors, and capacitors are all sufficiently fast and clean. Enter the "switched mode" power supply (SMPS).

As its name implies, the SMPS is a quintessentially digital device. At its core are switches that flip so fast that they are either fully open or fully closed almost all of the time, and almost never in the in-between states where lots of power gets dissipated. Capacitors, inductors, and transformers can be almost lossless too. As the switches boost frequencies higher, they also shrink the size of the transformers required. The switches also permit the use of much smaller, higher-voltage capacitors located on the upstream rather than the downstream side of the power supply. So the entire power supply gets very much smaller, lighter, and more efficient.

Proposed designs for new circuits that would eventually be incorporated in the SMPS began to proliferate rapidly soon after the invention of the transistor in 1948. The advent of germanium power transistors in 1952 gave further impetus to these developments. Low voltage DC-to-DC devices were developed in the '60s, mainly for the aerospace industry, which placed a high premium on small size and high efficiency. SMPS development for the commercial market—particularly for televisions—got its first big boost with the advent of fast, high-voltage silicon switching transistors in 1967. The limits to how far SMPS designs could be pushed remained centered on the switching transistors. High-voltage (above 500 V) transistors weren't readily available, nor were transistors that could handle the high currents required for higher power devices.

Theoreticians at Caltech then developed new tools for analyzing the performance and stability of SMPS designs, and these tools made it possible to design much more complex devices, using multiple switches that could collectively handle much higher power. The power MOSFETs introduced at the end of the 1970s were very much faster and much more efficient than the bipolar junction transistors that they superseded. MOSFETs could only be used up to about 500 V, however. IGBTs arrived in the 1990s; they are as efficient as MOSFETs, though not as fast, and can handle much higher voltages and much more power.

As a direct result, the market for power supplies is now being fundamentally transformed.

First Telecom—Now the Rest

The starting point for this newsletter over two years ago was a simple one: digital devices can't run directly off the grid; they require altogether new and different forms of power. Two of our early issues addressed the bricks that go on to server motherboards and the silicon power plants that supply half a megawatt of power to room-sized arrays of digital electronics (*Silicon Power Plants,* June 2000).

The market for power supplies is now being fundamentally transformed

With computers and telecom, the digital loads determine what the power supplies must deliver, and determine it early on in the design cycle. Power-supply vendors must track the power specifications set out by the manufacturers of microprocessors, radio-frequency chips, and solid-state lasers. The voltages at which these semiconductor devices run are determined by the basic chemistry and physics of the materials and by how finely the engineers can build gates and resistors on the surface of the chip. All of these specifications get set a year or more before the mass-produced devices begin tumbling out of the fabs. This forces a high degree of electrical standardization on every product built around these devices.

An additional factor in markets for telecom equipment is that the hardware is networked. When the links are electrical, as they are on conventional twisted-pair telephone lines, voltage and current specifications have to be harmonized across central-office switches, line cards, high-speed digital subscriber lines, telephones, and DSL terminals on the customer premises. So this again forces a high degree of electrical standardization across the network.

These factors strongly favor outsourcing to, and consolidation of, independent power-supply manufacturers. They thus explain why telecom equipment vendors, after years of building their power supplies in-house, have almost all spun out those units.

These same factors have not, however, turned data and telecom power supplies into simple commodities that anyone can build, in a market defined by nothing but cut-throat price competition. Quite the contrary, in fact. The voltage and current requirements prescribed by the chip manufacturers and the network are very transparent, but they are also very demanding. As we have described before, digital loads change very rapidly—so rapidly that the final layer of power-conditioning hardware has to be located very close to the final load, otherwise the resistance and inductance of the wires separating the two corrupts the power before it gets to where it's needed. Thus, even as they have become standardized, the power-supply requirements for high-end data and telecom equipment have become increasingly demanding. There is a high premium placed on building smaller, faster, more compact, more efficient (i.e. cooler) units.

Until quite recently, there were no comparable forces simultaneously driving both standardization and rapidly improving performance in the power supplies required for electric motors or lights. Lights were built around the truly old, analog technologies of glowing filaments and fluorescing gases. The motors were used mainly to spin shafts and compress hydraulic and pneumatic fluids, with most of the control lodged downstream in click-click bang-bang arrays of valves, push-rods, and so forth (*Powerchip Paradigm II: Broadband Power* Special Report). Now this world is changing rapidly as well.

Solid-state light-emitting diodes and lasers are rapidly displacing the old "gas lamp" universe—new power supplies are needed for these lights—and also enable new forms of lighting control that weren't possible at all with the older technologies. And silicon-controlled direct-drive motors are moving very close to the final loads, and require fast, very precise power supplies to deliver high-precision motion control.

Power supplies are multiplying under the hood of the car, as well. Detroit is standardizing on a new 42 V DC electrical bus, and dozens of new electrical loads are multiplying around it: microprocessors for logic, motors to drive electric fans, valves, brakes, and steering modules, additional power supplies for the solid-state lights in video displays, the rest of the passenger cabin, the tail lights, infrared imaging systems, and on-board radar. Multi-voltage units power clusters of loads, but the power supplies themselves also multiply. An architecture of tiered grids and voltages makes the most sense for distributing power efficiently without piling on pounds of wiring, and the smallest power supplies have to be located close to the final loads if they are to deliver the high-power quality needed.

As power supplies multiply, they create new problems, which are solved by building better power supplies. Simple power supplies generate cacophonies of harmonic noise that propagate back up the grid. The noise dissipates power in the grid itself—which, at its worst, can burn out, and blows up generators and transformers, causing comparable problems for all other users drawing power from the same grid. Utilities and regulators have long required big users of power to implement "power factor correction" to eliminate these problems, and Europe is now in the process of outlawing linear power supplies above 75 W. And environmental groups worldwide are pushing for similar fixes because they significantly boost power-supply efficiency.

These trends create, all in all, an environment rich with opportunity for power-supply manufacturers—like Magnetek—that grasp what's going on. The power supply's "customers"—the downstream grids and loads that that make the power supply necessary—are coalescing around large but well-defined sets of voltage/current profiles, which are dictated, in turn, by engineering imperatives that are fairly transparent and predictable. Magnetek doesn't have to worry that Intel will suddenly switch to a 10-volt microprocessor, nor even that crane operators or appliance manufacturers will abruptly settle on new electrical parameters that will enrich one power-supply vendor and ruin another. And the company can count on the market always placing a premium on the power supply that packs more power into less space, that runs faster and more efficiently, that embodies a lot of digital intelligence, and that is wired from the inside out for digital control.

Today, most power-supply vendors are still much smaller than their component suppliers upstream, and their customers downstream—a reflection of the old world in which power supplies had to be designed customer by customer, and platform by platform, with the designer serving more as a contract engineer than a vendor of mass-produced hardware. This is now changing rapidly. All of the major trends argue for the emergence of small numbers of big, efficient, nimble, Dell-like, cross-platform SMPS manufacturers.

Magnetek

Magnetek was formed in 1984, through the acquisition of Litton Industries' Magnetics Group. We took a first look at Magnetek in late 1999—and quickly decided that the then $1.5-billion company was of little interest. At the time, some 80 percent of its sales were centered on the old, analog world of electric motors and ballasts for fluorescent lights. Motors still held some interest but most of the action lay in their power electronics and logic controllers (*Digital Movers,* February 2002 and *Networking the Digital Factory,* September 2001). Conventional magnetic light ballasts, we believed, were soon going to be superseded by power electronics, and then fluorescent lights themselves would give way to solid-state lights (*Quantum Power,* May 2001).

Magnetek's board had apparently reached similar conclusions. Between 1999 and 2001, the company shed two-thirds of its business—motors, generators, lighting ballasts, and transformers. During that same period Magnetek acquired J-Tec Communication Service and ADS to form Magnetek Telecom Power. What the company shed, roughly speaking, was everything anchored in the old world of analog power supplies. It emerged as a $200-million (annual revenues) largely debt-free pure play in digital power supplies. Magnetek now describes its business as "the marriage of analog power and digital electronics to produce optimum power solutions for data processing, communications, energy generation, and other demanding applications."

About two-thirds of the company's current revenues come from its Power Controls division, the rest from Motion Controls. The Power Controls group makes a wide range of AC-DC power switching and control modules, which it sells primarily to OEMs of high-tech data, telecom, laser, medical and power-generation equipment, and home appliances. Magnetek's sales to IBM center almost exclusively on power supplies for larger servers; Magnetek is one of a small set of tier-one IBM suppliers. In motion controls, Magnetek specializes in programmable, variable frequency power supplies used in industrial automation and materials handling, commercial heating, ventilating, and air conditioning. Here, too, Magnetek sells to OEMs, but it also makes complete power systems for a range of heavy lifters (like overhead hoists and cranes) and elevators, where it has 70 percent and 60 percent respectively of the global market.

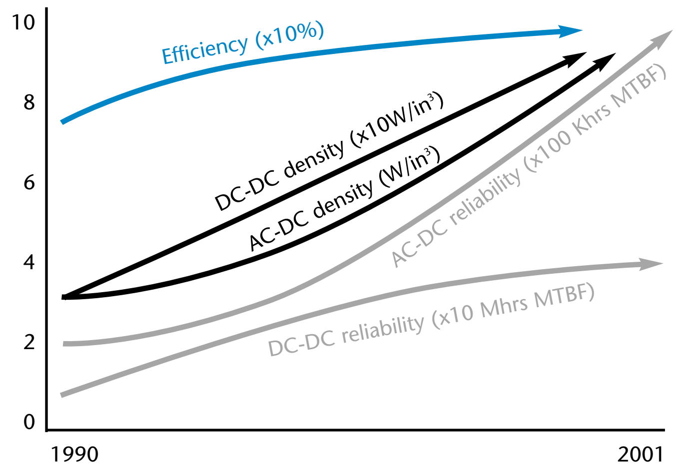
Magnetek's technology strategy was formulated by the company's CTO, Alex Levran, whose roots trace back to engineering one of the earliest uninterruptible power supplies at Teledyne. Levran brims with ideas, and is deeply knowledgeable about the major trends now redefining all power supplies, from the one-volt VRMs that address the extraordinary power demands of the next-generation logic chips to the kilowatt systems that power DC and AC elevator motors. As it happens, elevators are the one "transportation" sector where electric power is already in complete control, and elevator manufacturers are pushing power-supply technology aggressively to promote speed and comfort. Magnetek isn't talking about Detroit yet, but we're betting that at least some part of the company's technology will find its way into the hybrid-electric car (*The Silicon Car,* December 2000). Magnetek's ultra-dense, logic-driven battery charger is already in Dean Kamen's Segway "personal transporter" (*Digital Movers,* February 2002).

Digital power supplies are controlled by digital logic. In 1995, Magnetek purchased about 5,000 microcontrollers and DSPs for installation in its power systems; it purchases over 2.5 million today. Nearly 90 percent of its products now contain embedded logic. A typical Magnetek power supply contains about 5,000 lines of code, and about 30 percent of the company's units contain closer to 100,000 lines. These numbers help to explain why Magnetek's modular power supplies are so adaptable—they are relatively easy to reprogram to handle different loads. The company's power supplies are also rich with sensors, used to monitor the temperature and electrical leakage of capacitors, for example, which are generally a power supply's weakest link. Magnetek also embeds standard communications buses to dispatch alerts and receive control instructions.

Similar tools and capabilities are incorporated in the full range of Magnetek products. The company is bringing logic, control, and communications to the network of street lights in Holland, integrating software-intensive power supplies, status sensors, and communications functions into a unit that both powers the lights and continuously reports on the bulb's status via power-line carrier and wireless aggregation and up-link points. Magnetek is also developing for Europe's Valeo (a tier-one auto supplier) an ultra-dense power supply that drives the high-voltage, high-intensity metal-halide headlights found on BMWs, Benzes, and the like. To make the unit extremely compact, Magnetek built it around exceptionally fast and efficient MOSFETs, which make possible an industry-leading 1.2 MHz switching design. Magnetek also has the world's largest share of fuel-cell power conditioning systems, serving 100 installations with an aggregate 24 MW of generating capacity. The power conditioning hardware is the second most important factor in fuel cell design, after the daunting reliability and cost issues that beset all fuel cells.

About to receive UL approval, Magnetek's plug-com-

Impact of Silicon and Software on Power Supplies



Driven by the triad of better silicon, sensors, and software, power supplies have achieved record densities (DC-DC now hitting 100 W per W/in³, AC-DC beyond 10 W/in³), greater efficiency (up more than 10 percentage points in the decade), and greater reliability (AC-DC now over one million hours mean-time-between-failures (MTBF), and DC-DC over 40 million hours MTBF). All this while costs have dropped four-fold in dollars per watt. The trend continues.

patible DC circuit breaker is a soon-to-be-launched sleeper product that breaks new ground by extending digital power, logic, and software to the basic circuit breaker box. When a standard electromechanical breaker kicks open, it creates power ripples in the circuit which can cause serious problems in sensitive DC equipment (such as telecom equipment) fed by other circuits on the same bus. The all-electronic unit maintains voltage stability. A cluster of nearly two-dozen such breakers can communicate with each other, and can be coordinated from a common control point for load balancing, power sharing, harmonic control and for upstream status and alert signaling. As silicon costs drop and production volumes rise, silicon breaker technology will migrate into AC breaker boxes as well—those ubiquitous dull gray panels found on the wall of every home and building that connects to the grid. Yet another Edison-era technological legacy will make the leap from slow, dumb, analog safety switch to smart, digital load management and conditioning.

Magnetek is now ideally positioned to bring its core design skills to bear across a wide range of power-supply platforms. It is an industry leader in thermal management, a key factor in shrinking size and extending product life. Much of the ingenuity here centers on designing circuits that switch in very precise synchrony with incoming AC power, so that the key action happens exactly when the voltage crosses zero. This sharply reduces the amount of power dissipated during switching. Magnetek has also patented thermally conductive coatings and materials that make it possible to pack components more densely. Magnetek's emphasis on modular, programmable designs lets the company deliver products that meet new customer design specifications very much faster, accelerating speed-to-market. The company also has tremendous production flexibility—it can manufacture from small quantities to volumes in the millions.

Pure Play

The power-supply industry is now coalescing into three main sectors: low-cost, low-power commoditized linear power supplies; defense/aerospace with highly specialized requirements; and switch mode units for everything else in the middle. Most power-supply revenues, and the greatest revenue growth, lie in this middle ground.

Linear power supplies are very cheap; they completely dominate the low-power end of the market, serving under-20W cell phones, PDAs, toys, and so forth, and they retain substantial market shares up to about 100 W. Many are made in China—by Taiwan-based Phihong or Delta, for example. At the other end of the market, military contractors are aggressively developing advanced power supplies as digital and communications technologies proliferate in every imaginable type of battlefield hardware. In our first issue for subscribers (*The Law of the Powercosm,* April 2000) we noted that the Office of Naval Research has a Power Electronics Building Block (PEBB) program focused on the development of standard power modules that can be stacked and assembled for use in an all-electric ship.

Advanced Energy Industries (AEIS) is a significant specialist worthy of note as well—it makes power supplies used in semiconductor fab equipment, selling mainly to companies like Applied Materials, Novellus, and Veeco (*Building the I^2C,* July 2002). There are several small, clever, creative (and private) players in the market too: Satcon (one of its three business groups is focused on power supplies, discussed in *Silicon and Lead,* July 2001); Pioneer Magnetics (inventor of the original patent for power factor correction); Diversified Technologies (manufacturers of an all-digital transformer and a serious, if small, defense supplier); Xantrex (which is chasing the consumer, home, truck, and renewable energy markets for power supplies); and Schaefer (Germany).

In the broad middle of the power-supply market, and in particular the switch mode designs, Magnetek ranks among the dozen or so top-tier vendors. Others in the top of the field include industry giants Tyco, Delta Electronics, Emerson Electric, Celestica, Lambda (owned by Invensys), as well as Ascom Energy Systems (part of the $2 billion Swiss conglomerate), Power-One, Vicor, Ascom, Artesyn Technologies, Transistor Devices, Peco II, Marconi, and C&D Technologies (a big player in back-up battery charging [*Silicon and Lead,* July 2001]).

The power-systems unit that Lucent sold to Tyco in 2000 is a giant in the industry, but a pure telecom/data play; it also accounts for under 5 percent of Tyco sales, so there's no way to invest in it directly. Delta Products, a Taiwan giant, makes lots of other stuff too (motor drives, logic controllers, ballasts, TVs, video displays); power supplies account for only about 30 percent of its sales. In the top-tier segment of the civilian market for truly digital power supplies, nearly all the big vendors are either locked primarily into telecom markets, or else they're only tiny divisions within much larger, highly diversified companies.

With IBM as its leading customer, Magnetek certainly has a significant stake in the health of datacom markets too. But unlike two other power-supply companies we've addressed before, Magnetek has extended what began as computer-centered power supply-expertise into a wide range of other digital-power markets, and this strategy clearly distinguishes it from most of the other players in the field. With an all-digital focus, and products spanning a wide range of power levels and industries, Magnetek stands out as the only significant manufacturer with state-of-the-art technology, an all-digital line of products, and very little in the way of extraneous baggage in other products and markets. Among the top-tier companies, only three other players arguably have comparable market scope: Lambda, Delta, and Astec (owned by Emerson). All make first-rate products, and all sell industrial, medical, instrumentation power supplies, but all appear to get most of their revenues from telecom and data markets. And for all of those companies, power supplies comprise only a small part of total sales.

General Purpose Power Processor

The SMPS market is now defined by three fundamental, overarching trends.

First, semiconductor switches continue to evolve rapidly. Each new generation of device can handle more power and more current, faster and more efficiently, and prices fall relentlessly as the manufacturers of power semiconductors ride on the declining-cost coattails of the logic semiconductor industry. The efficiency of power MOSFETs in recent years has improved five-fold in the past five years alone. Switching frequencies rose to 300 kHz by the mid-1990s. Multilayer capacitors continue to improve very quickly too, as fabrication techniques improve and new architectures and materials are developed. Five years ago, most commercial SMPSs operated in the 10-kHz to 50-kHz frequency ranges. Switching frequencies of 200 kHz and above are now common, and megahertz frequencies will be routine before long. Faster components make possible smaller power supplies. Since 1994, DC-DC power-supply density rose from 20 to 100 W per cubic inch, AC-DC power supplies from 2 to 10. At the same time, the cost of a typical, mid-range power supply dropped from about $0.80 per W to below $0.20 per W.

Second, software accounts for a steadily growing fraction of the SMPS design and operation. By incorporating more MOSFETs and IGBTs, the SMPS designer can build a smaller, faster, more efficient device. But the increasingly complex circuit topologies require increasingly sophisticated CAD/CAM analysis and design tools. Equally sophisticated software is used to analyze thermal problems, which grow increasingly important as more power supply is packed into less space. In their operation, the new circuit topologies support new control strategies—pulse train (as opposed to pulse width) modulation, current-mode control, feed-forward techniques, and so on. These control algorithms are implemented in custom-designed integrated circuits that also incorporate protective and monitoring circuits such as current limit, over-voltage protection, and soft-start-up. Though ultimately embodied in hardware, almost all the value of the controller lies in the code.

Tomorrow's power supplies will be so compact and efficient from the get-go that they can be dropped into devices on a plug-and-play basis

Third, SMPS performance is moving far out ahead of the systems that the SMPS serves. As a direct result, the SMPS is making the transition from "application specific" device to "general purpose" power processor. Essentially the same device can be used across an ever-widening range of platforms and loads. The trend here directly mirrors what occurred with embedded logic a decade earlier. While dedicated, custom-designed logic circuits are still used in the most demanding settings, the same general purpose microprocessor now lands in a very broad range of devices and platforms, because it has grown so fast, powerful, compact, and cheap. Yesterday's power supplies had to be custom-designed to improve efficiency and save space. They had to be tuned and matched to the precise platform and load at hand. Tomorrow's will be so compact and efficient from the get-go that they can be dropped into devices on a plug-and-play basis. The core engineering skills required to design and manufacture the SMPS in this new environment cut broadly across SMPS markets; they are no longer tightly tied to the final platform in which the SMPS will land.

In sum, the SMPS is on the same trajectory today as the "switched mode logic supply" —i.e. the computer—was on two decades ago. SMPS manufacturers now face the same technological and market imperatives that created Intel, Microsoft, Oracle, and Dell. Software of one form or another defines a rapidly growing fraction of the value of the final device. The component hardware is evolving rapidly. Product cycles are accelerating, and fast time to market is essential to success. But there are, at the same time, very large economies of scope and scale.

Perhaps three or four large players have fully grasped the significance of these trends, and are adapting their product lines and marketing strategies accordingly. All are building much smaller, more compact, higher power, higher efficiency, modularized, standard-

Ascendant Technology	Company (Symbol)	Reference Date	Reference Price	7/26/02 Price	52wk Range	Market Cap
System Integrators	Magnetek Inc. (MAG)	7/26/02	6.49	6.49	6.49 - 12.73	146.2
	Veeco Instruments (VECO)	6/28/02	23.11	12.69	12.40 - 41.70	368.6m
	Oceaneering Intl (OII)	5/31/02	31.01	21.40	13.96 - 32.17	526.3m
	Amkor Technology (AMKR)	4/2/02	21.85	3.94	3.62 - 24.79	646.3m
	Emerson (EMR)	5/31/00	59.00	49.18	44.04 - 66.09	20.7b
	Power-One (PWER)	4/28/00	22.75	4.72	4.20 - 17.40	373.4m
Electron Storage & Ride-Through	Kemet Corp. (KEM)	5/1/02	19.63	12.14	12.38 - 22.40	1.1b
	Wilson Greatbatch Technologies (GB)	3/4/02	25.36	23.85	21.20 - 39.00	499.3m
	C&D Technologies (CHP)	6/29/01	31.00	14.16	13.25 - 32.15	367.9m
	Maxwell Technologies (MXWL)	2/23/01	16.72	7.25	5.81 - 21.50	78.0m
	American Superconductor (AMSC)	9/30/99	15.38	5.35	3.85 - 19.25	109.9m
Project, Sense, and Control	Danaher Corp. (DHR)	1/29/02	61.56	58.95	43.90 - 75.46	8.9b
	FLIR Systems (FLIR)	1/9/02	41.64	40.25	25.00 - 59.50	673.0m
	Analogic (ALOG)	11/30/01	36.88	39.74	33.40 - 56.50	526.9m
	TRW Inc. (TRW)	10/24/01	33.21	50.53	27.43 - 57.90	6.4b
	Raytheon Co. (RTN)	9/16/01*	24.85	29.80	23.95 - 45.70	11.9b
	Rockwell Automation (ROK)	8/29/01	16.22	17.03	11.78 - 22.79	3.2b
	Analog Devices (ADI)	7/27/01	47.00	22.10	21.80 - 52.74	8.1b
	Coherent (COHR)	5/31/01	35.50	21.80	20.95 - 39.50	629.5m
Powerchips	Cree Inc. (CREE)	4/30/01	21.53	14.22	10.35 - 33.32	1.0b
	Microsemi (MSCC)	3/30/01	14.00	5.31	5.22 - 40.10	153.3m
	Fairchild Semiconductor (FCS)	1/22/01	17.69	17.30	13.76 - 32.03	2.0b
	Infineon (IFX)	11/27/00	43.75	14.25	10.71 - 27.55	9.9b
	Advanced Power (APTI)	8/7/00	15.00	9.98	6.50 - 15.25	103.4m
	IXYS (SYXI)	3/31/00	6.78	4.79	4.11 - 14.44	151.6m
	International Rectifier (IRF)	3/31/00	38.13	22.54	21.25 - 50.50	1.4b

Note: This table lists technologies in the Digital Power Paradigm, and representative companies that possess the ascendant technologies. But by no means are the technologies exclusive to these companies. In keeping with our objective of providing a technology strategy report, companies appear on this list only for the core competencies, without any judgment of market price or timing. Reference Price is a company's closing stock price on the Reference Date, the date on which the Power Panel was generated for the Digital Power Report in which the company was added to the Table. All "current" stock prices and new Reference Prices/Dates are based on the closing price for the last trading day prior to publication. IPO reference dates, however, are the day of the IPO. Though the Reference Price/Date is of necessity prior to final editorial, printing and distribution of the Digital Power Report, no notice of company changes is given prior to publication. Huber and Mills may hold positions in companies discussed in this newsletter or listed on the panel, and may provide technology assessment services for firms that have interests in the companies.

* *The October 2001 issue closed on September 16, 2001 and was posted at 8 a.m. on September 17, 2001. Due to the markets' close in the week after September 11, our reference price reflects Raytheon's closing price on September 10, 2001.*

ized, scalable, programmable power supplies. The industry as a whole can now be expected to deliver, within a few years, a ten-fold increase in power-supply power density—to perhaps 10,000 W per pound of power supply, and well beyond 100 W per cubic inch. For that to happen, conversion efficiencies will have to rise another 5 percentage points (to above 95 percent), otherwise the thermal problems become unmanageable. Extremely high efficiency is equally essential to reduce platform weight and power consumption. And with power supplies multiplying rapidly, prices must, and will, continue to fall.

If the competition is intense, the market is already huge, and growing very rapidly. The process of electrification continues to accelerate in factories, cars, ships, and every other major sector of the economy that isn't already electrified. The new loads are rich in digital logic, and depend on high-precision control. Demand for power supplies is therefore rising rapidly. Magnetek's technology and marketing strategy put it in an ideal position to ride this wave for decades to come.

Peter Huber and Mark Mills
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