The Power Conversion Process as a Prosperity Machine
Part II — Power Semiconductor Road Maps

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Last year, I prepared a paper about the role of power conversion in the broadest possible context: power conversion as an instrument for change [1]. To recap very briefly: the laws of supply and demand ultimately set the price of goods and services, but the cost of energy determines the underlying cost of everything we produce. As a process that makes electrical energy more efficient and affordable, power conversion allows us to raise the worldwide standard of living and conserve our natural resources. This fundamental win-win proposition lies at the heart of my view of power conversion as an engine for prosperity. Today, I'd like to look at a few of the applications that can benefit most from the adoption of power conversion and examine some of the developments that will accelerate the adoption of power conversion technology.

Total global consumption of all types of energy was 33×10^{12} KWH in 1994 [2]. About 23 percent of that — or about 8×10^{12} KWH — is electricity [3]. Interestingly, from 1970 to 1983, the growth of energy consumption averaged about 1 percent, but from 1983 to 1993, the growth rate nearly doubled. As environmental and other concerns slow the growth of electrical energy generation in coming years, it becomes essential that we conserve and use this limited and precious resource more efficiently.

Conserving electricity and making it a better fuel relies on the widespread adoption of the power conversion process, which takes electricity from a source, such as the electrical wall socket or a battery, and converts it to a form exactly suited to the electrical load. This process is analogous to what the oil refinery does to convert crude oil into various forms of efficient petrochemical fuels.

International Rectifier views this process in four stages as shown in Fig. 1. In the first stage, raw power from an AC source is converted to an unregulated DC. MOSFET switches receive signals from the control stage to chop the energy into small packets that are reconfigured by the output stage and tailored to the electrical load.

Sales of semiconductors used in the power conversion process were $8.1 billion in calendar 1997 [4]. During that year, only about 16 percent of the world's electrical power applications used the power conversion process at all [5]. With electricity consumption rising, the opportunity for long-term growth in our industry is virtually assured.

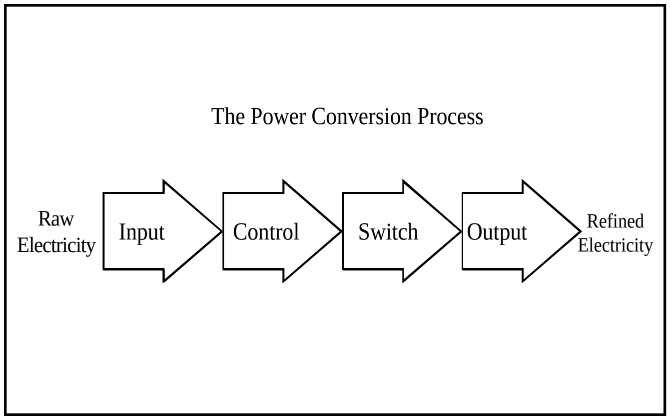

Fig.1. The Four Stage Power Conversion Process

THE BENEFITS OF THE POWER CONVERSION PROCESS

Let's take a brief look at three of the applications that drive the growth of power conversion. According to EPRI, the largest single application by far is motors at 55 percent of all electricity consumed, followed by lighting at 21 percent. Power supplies of all types for electronic equipment in consumer, communications and computing equipment accounts for about 6 percent of electrical consumption[18][19][20].

By using the power conversion process to shift from incandescent to electronic fluorescent lighting, we can reduce energy consumption by about half [6]. By replacing our dumb, uncontrolled motors, we can save as much as 40 percent of their electricity consumption. This is electrical energy that we'll need to accommodate population growth and the demand for a higher standard of living as we enter the next century. Conservatively assuming a cost of just ten cents per KWH, energy saved in just these two applications will boost the world economy by about $200 billion annually (see appendix A).

Let's look at some specifics. A typical refrigerator today uses an uncontrolled DC motor to power the compressor. Based on our discussions with refrigerator compressor manufacturers, by the year 2003 10 percent of the 133 million refrigerator compressors produced annually will convert to using variable speed AC motors that cut energy consumption by about 40 percent [7]. For a typical 20 cubic foot unit, this cuts a household electrical bill by about $70 per year. In year 2003 this represents a $900 million energy savings from just one motor drive application.

Lighting represents about 21 percent of current electrical consumption [8], and the lamp of choice worldwide is an incandescent bulb powered directly from an AC main. In 1997, 350 million electronic compact fluorescent lights were sold [9] as compared with over 10 billion incandescent bulbs [17]. These lights use about 75 percent less energy than incandescent bulbs for the same illumination level, saving users from $30 to $70 in electricity over the life of the bulb. This is another success story, already saving $1 billion in energy annually (see appendix A).

Advanced power conversion semiconductors save space, reduce cooling requirements, and eliminate between 5 and 10 percent of the system losses in power supplies for computers, network servers, and telecommunications equipment. This saves at least another $2.5 billion per year in energy by 2001 (see appendix A).

Power conversion will also drive electricity into more and more applications to replace mechanical devices or petrochemical energy. We are developing automotive systems that eliminate cumbersome belts and timing chains and produce large gains in fuel economy, assembly cost, and reliability. Electric steering that replaces bulky hydraulic systems and improves fuel economy by five percent [10] will start to appear in volume in model year 2000 (see Fig. 2). Integrating the starter and generator motors can eliminate one belt and a heavy electric starter motor, while converting electricity more efficiently than alternator diodes and improving fuel economy by 5 to 10 percent [11]. Timing chains are next — with a similar improvement in engine performance. Add to these examples the migration to a more efficient 42 Volt distribution system, and the power conversion process is driving a 15-20 percent boost in fuel economy in the average car over the next 10 years.

Let's examine the key developments in semiconductors that will enable these applications to flourish.

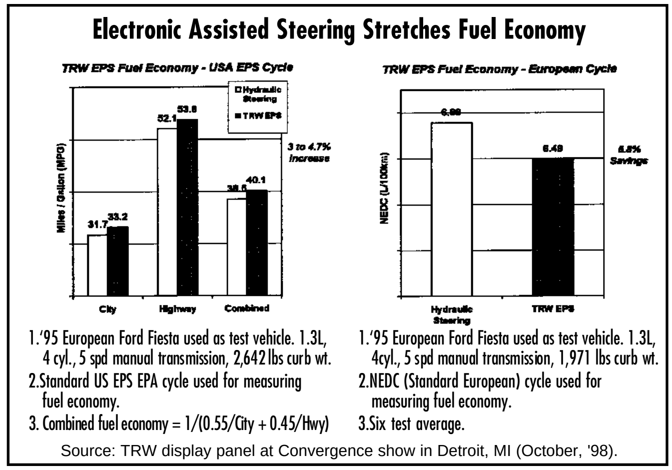

Fig. 2. Estimates of Fuel Savings From Electronic Power Steering

Standardized Architecture

One of the biggest boosts to the adoption of power conversion comes from standardizing system architecture and offering analog Integrated Circuits that embody these architectures. Thousands of companies around the world reinvent the wheel daily as they each design largely undifferentiated motor drives, power supplies, lighting ballasts, and other power conversion circuits. By adopting standard architectures, this analog circuit design time can be saved and put to higher value-added activities.

In motor drives, high voltage ICs to be introduced in the next six months allow motor drives under 7.5KW to be built with one digital IC, one high voltage analog IC, and one power stage module (see Fig. 3). The motor drive designer can focus all his or her effort on adding features that differentiate the product. Changes to design can be made with software instead of a soldering iron. Time-to-market shrinks to fit short product life cycles, and the adoption of variable speed motors accelerates.

In lighting ballasts a similar evolution is underway. Standardized market requirements for fluorescent bulb safety, longer product life, greater efficiency, power factor correction, reduced noise emission, and other advanced features have led to a standard series of high voltage ICs (see Fig. 4). These devices are "digital ready," so features such as dimming or environmental control system interface can be added quickly and inexpensively. No need for analog design. Save the time for feature enhancement and cost reduction.

Distributed board-mounted power is changing the complexion of the traditional "silver box" from a multi-output AC/DC converter to a single output (48V) pre-regulator including power factor correction (see Fig. 5). This opens up the possibility of standardized circuit topologies and integrated circuits that meet efficiency and noise requirements without costly custom analog design. New power supply architecture standards are also needed to accommodate output voltages

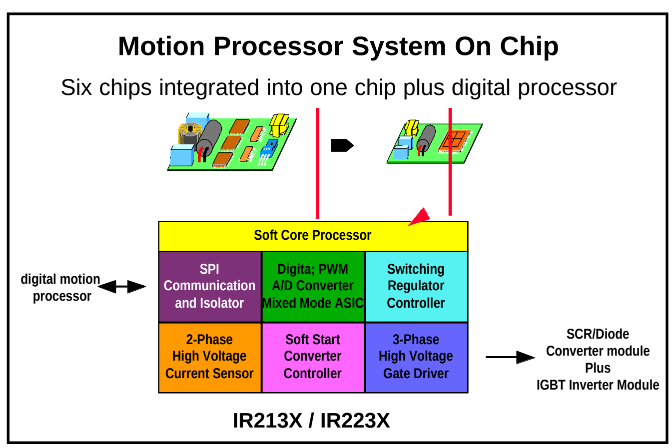

Fig. 3. Motor Drive Architecture Evolution

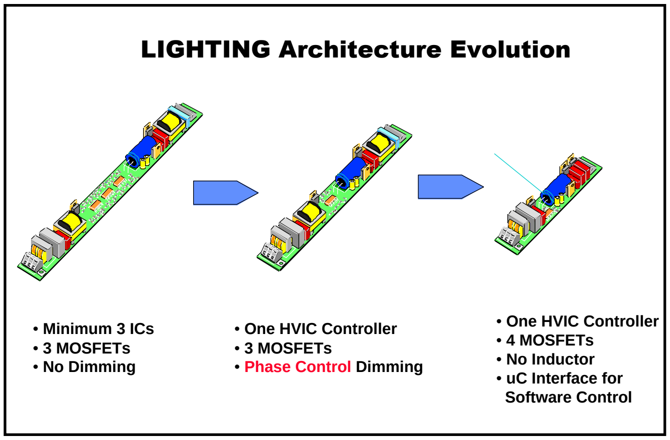

Fig. 4. Lighting Architecture Evolution

dropping below 1 Volt with greatly increased current requirements (see Fig. 15). Integrated Circuits from International Rectifier will eliminate much of the design effort needed to make the transition from diodes to synchronous rectifiers.

Automotive architecture is also in a state of rapid change. In the next few years the power in a car will probably be distributed at 42 Volts instead of 12 Volts [12]. This creates an opportunity for standardized architecture that can save billions of dollars of automotive and semiconductor engineering. The leaders in this field need to standardize early in order to realize this gain.

Packaging

In the field of power conversion packaging, increasing power conversion density poses the central challenge — in essence, to put more and more silicon in smaller and smaller packages. Over the last year, we have achieved major packaging advances for individual components and now offer a family of 'Super' packages in both heat-sinkable (through-hole) and surface-mount configurations which double the

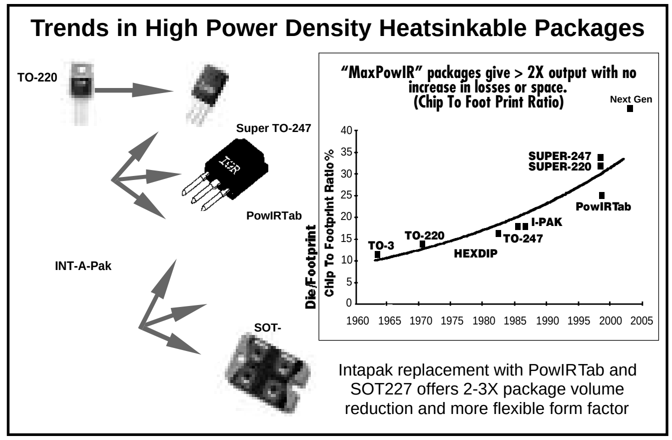

Fig. 6. New Heat-Sinkable Package Outlines Double the Density of Power Stages for Power Supplies and Motor Drives

die-to-footprint ratio to 30 percent or more, while cutting internal resistance in half and permitting dramatic increases in power density for power supplies and inverter motor drives (see Fig. 6, 7 and 8).

Many of the breakthrough gains in power conversion density in the next year or two will come from radically different packages such as the "3-Dimensional package" shown in Fig. 9. Chipscale packages, shown in the same figure, also offer an opportunity to include multiple device types in a single package with densities about double the current state-of-the-art.

For high-volume applications, integrating power devices, signal devices, and passive components can lead to great density improvements. Adaptable Planar Modules such as the one shown in Fig. 10 have achieved record power densities in variable speed motor drives.

Semiconductors

For the switch function (MOSFETs and IGBTs), improvements in overall switching efficiency will continue at a signif-

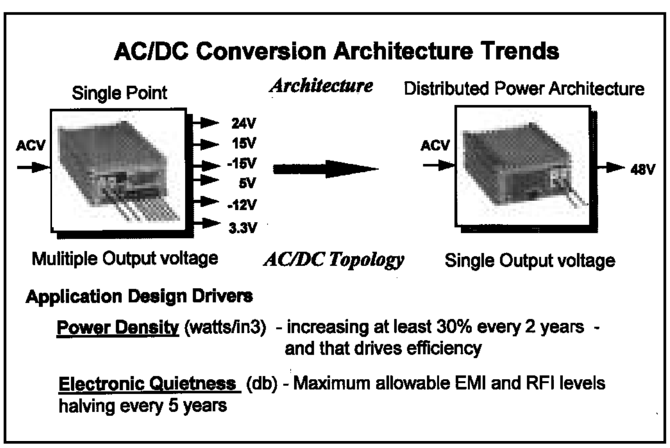

Fig. 5. Power Supply Architecture Evolution

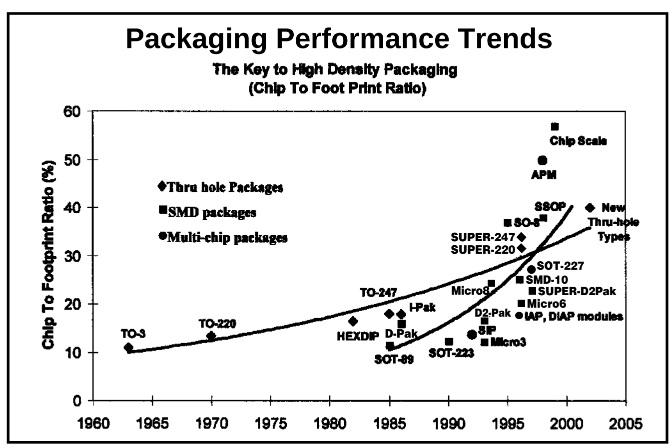

Fig. 7. Trend in Package Die-to-Footprint Ratio for Heat-Sinkable, Surface Mounted, and Multi-Chip Packages

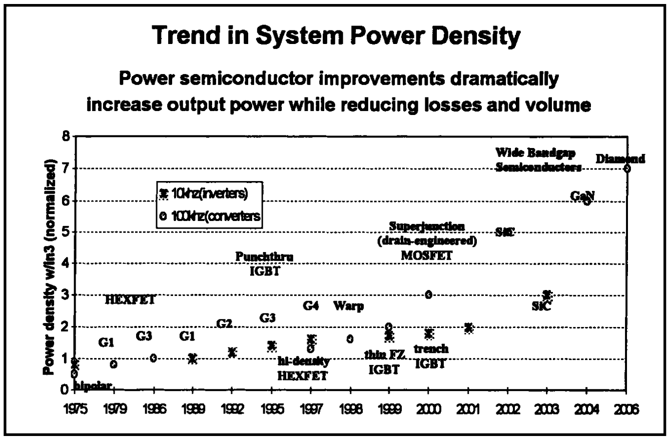

Fig. 8. Trend in Power Density for Inverters and Power Supplies

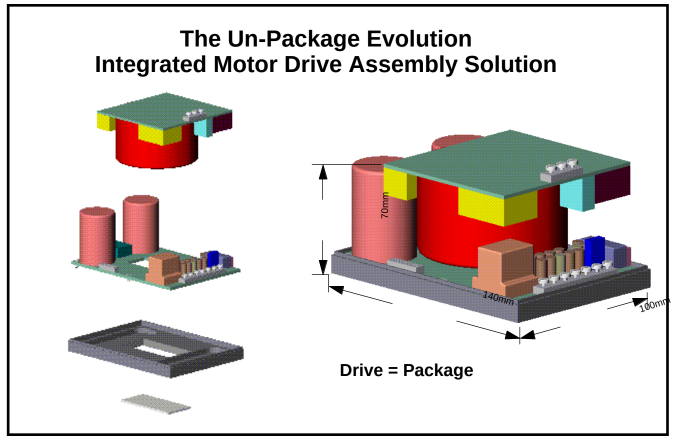

Fig. 10. Adaptable Planar Modules are Used to Achieve Benchmark Motor Drive Power Density

icant pace. For example, from 1997 to 2000, $R_{DS(on)}$ values for MOSFETs will show a threefold improvement for low voltage devices (see Fig. 11 and 12). Improvements in on-resistance accrue from higher cell densities, shorter channels, thinner gate oxides and lower substrate resistance through lower-resistivity materials and thinner wafers. Switching-loss improvements accrue from narrower ploysilicon lines and trenches, coupled with shallower junctions. In fact, as switch silicon improves, controlling and reducing losses from copper and aluminum in packages becomes increasingly important.

For IGBTs, progress will continue in the fundamental trade-off between $V_{CE(on)}$ and E_{ts}, with higher switching speeds achieved by controlling the injection level and minority carrier lifetime. Higher density designs and self-aligning processes will deliver lower and better-controlled $V_{CE(on)}$. The development of non-punch-through designs using bulk float zone materials, a low injection efficiency anode, and thinned wafers drive further improvements (see Fig. 13).

For the functions handled by diodes, we can project two major trends. First, shorter reverse recovery time (T_{rr}) for diodes that generate less noise. Here, faster soft recovery (without overshoot) will significantly improve the EMI characteristics of an input stage, including power factor correction, and allow new designs to meet or exceed new international noise standards like EN 61000-3-2 without extensive circuit redesign or added components (see Fig. 14). Second, improvements in MOSFET technology will convert many traditional output diode applications to synchronous rectification topologies (see Fig. 15). As a result, expect only modest future growth in the traditional diode market.

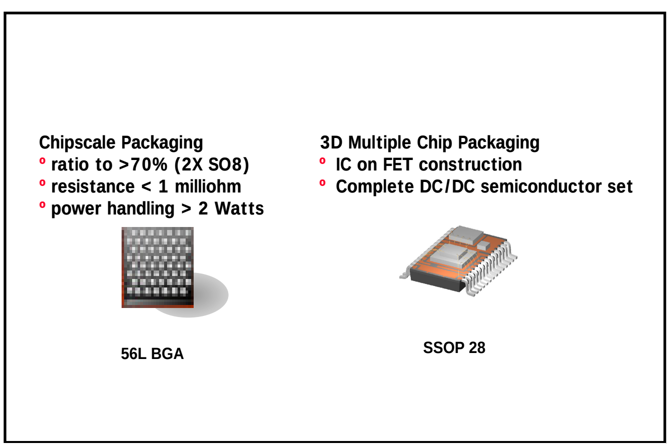

Fig. 9. 3-D Package and Chipscale Package Innovations

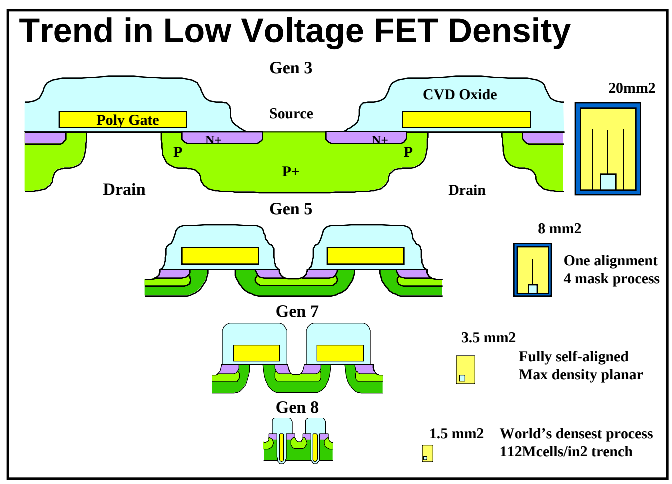

Fig. 11. High Density MOSFETStructures

CONCLUSION

By advancing the current state-of-the-art in power conversion, International Rectifier expects consumption of power conversion semiconductors to double by 2006 to over $16 billion annually. The value saved will continue to improve the world's standard of living: billions of dollars that would otherwise be wasted will be freed for investments in education, health care, agriculture, economic development, communications, and the arts. Seventy-two billion dollars can be saved annually by replacing all dumb motors with variable speed versions. One hundred nineteen billion dollars can be saved using advanced ballasts for lighting. We estimate savings in the power supply market at over $2.5 billion per year (see appendix A). In the automotive arena, power conversion systems that increase fuel economy will save 85 billion liters of gasoline a year or about $29 billion (see appendix A).

Well over $200 billion saved each year! This equals 30 million barrels of oil per day! It is up to us — the pioneers in power conversion — to make this happen.

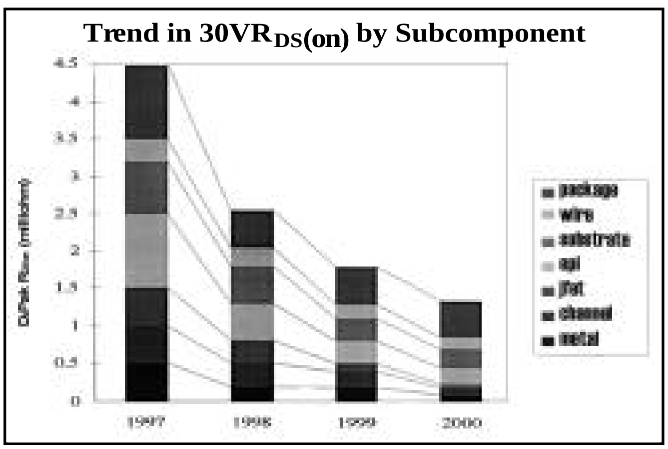

Fig. 12. Elements of MOSFET On-Resistance

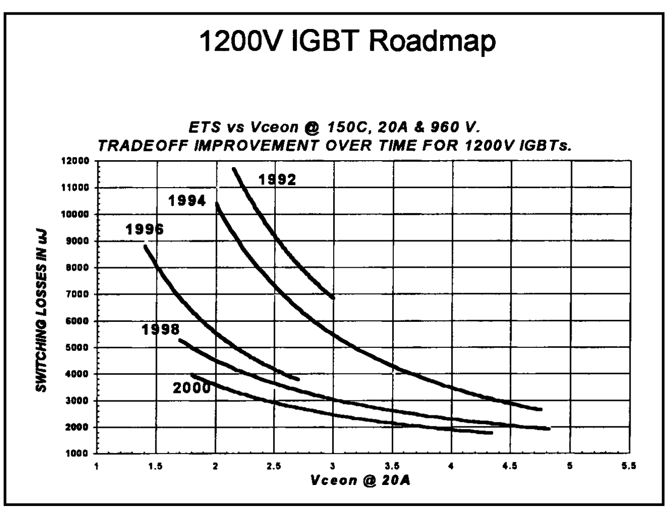

Fig. 13. IGBT Performance Evolution

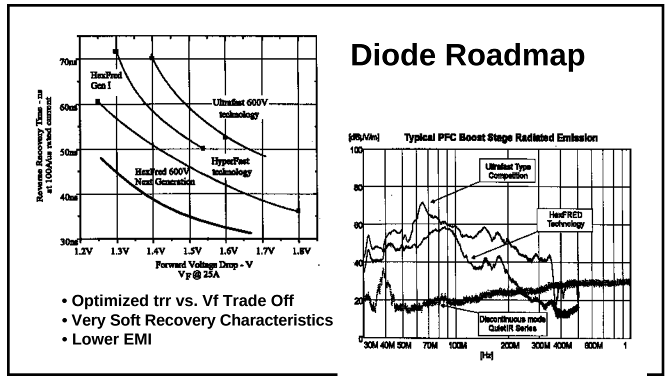

Fig. 14. Diode Performance Evolution

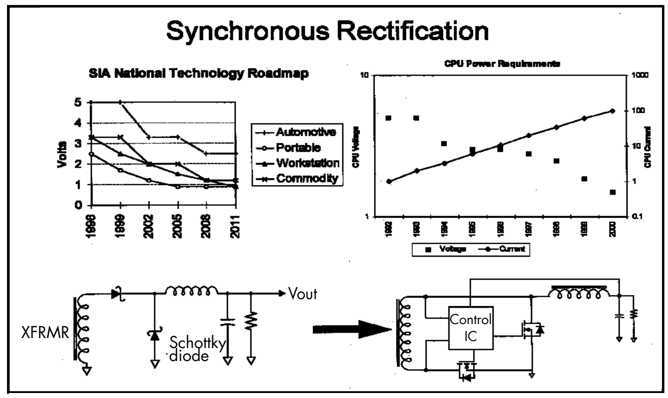

Fig. 15. Synchronous Rectifier Topology

Reference

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[2]The World Almanac and Book of Facts - 1997

[3]Energy Information Administration

[4]WSTS

[5]International Rectifier Estimate

[6]The International Association for Energy Efficient Lighting - www.stem.se/iaeel

[7]Based on measurements made by leading manufacturer of compressors who wishes to remain confidential

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Appendix A

Calculation of Energy Savings Potential

POWER SUPPLIES

1. Assume a 50 percent power utilization factor and that power supplies are used 50 percent of the time. Fifty nine billion watts of continuous power then becomes 130 billion KWH per year for one year's production usage [18].
2. Assuming half the power supplies made in the last 10 years are still in service and that the power supply market has been growing at an average of 15 percent annually. This calculates to 496 billion KWH per year converted by power supplies [20].
3. Assume a savings of 5 percent due to improvements in power conversion semiconductors and packaging.
4. Assume electrical costs of $0.10 per KWH.
5. Using #2, 3 and 4 above, the annual savings potential is $2.5 billion.

LIGHTING [6]

1. As per tables A1 & A2, U.S. savings potential by complete conversion to electronic fluorescent lighting would be $21.5 billion per year.
2. U.S. lighting consumption is 20 percent of the global consumption [17], the annual savings potential is $119 billion.

MOTOR DRIVES

1. Annual World-Wide Electric Motor energy usage is approximately $4X10^{12}$ KWH [13].
2. Percent of energy used by Electric Motors using efficient semiconductor-based drive is approximately 40 percent [14].
3. Estimated savings by converting to a variable speed, semi conductor-based motor drive is approximately 30 percent [15].
4. Estimated cost of a KWH = $0.10.
5. Combining 1, 2, 3 and 4 yields a potential savings of $72 billion per year.

AUTOMOTIVE

1. Over 500 million active vehicles in the world. New car production is over 50 million per year [16].
2. Average fuel consumption per passenger car per year in the U.S. is approximately 2.6K liters at an average of 16 miles per gallon [2].
3. Assume world-wide average is closer to 25 MPG yielding an estimated 1.7K liters per car per year.
4. World-wide consumption of fuel per year is therefore approximately $850x10^{9}$ liters per year.
5. Assuming a gasoline price of $0.34 per liter (Average prices world-wide are somewhat higher than this) and a 10 percent fuel savings if all cars used energy-savings solutions such as EPS and ISAD, the annual savings potential is greater than $29 billion. If only new car production is considered, the savings would be greater than $3 billion per year per year.

TABLE A1 [18][19]

1998 Power Supply Production

AC/DC	Power Range (watts)	150	300	500	750	1000	Total
	Ave. Watts	45	175	335	625	800	
	MU	276	106	34	11	8	
	MW	12442	18580	11238	6968	6097	55325
DC/DC	Power Range (watts)	50	100	150	250	500	
	Ave. Watts	25	50	75	125	250	
	MU	28	17	8	8	3	
	MW	700	871	609	995	726	3901
Total	MW						59226

TABLE A2

U.S.	Year	Total Electricity for Lighting	Savings Potential	Growth Rate	1999 Lighting Energy	KWH Saved	$ Saved
Residential	1993	$90.8X10^{9}$	57%	3%	$101.7X10^{9}$	$61.1X10^{9}$	$6.1X10^{9}$
Commercial and Industrial	1992	$352X10^{9}$	39%	3%	$394.2 X10^{9}$	$153.8X10^{9}$	$15.4X10^{9}$
Total		$442.8 X10^{9}$			$495.9X10^{9}$	$214.8X10^{9}$	$21.5X10^{9}$