WHERE ARE POWER SUPPLIES HEADED?

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***Abstract*: The invention of the transistor over fifty years ago, and the many advances in power semiconductor devices that followed have rapidly pushed switching power supplies to a ubiquitous presence in today's electronic world. Improvements in circuits, packaging and other components have also kept pace, helping make power supplies much smaller, cheaper and reliable. These advances are examined in three broad areas, powering architectures, ac/dc rectifiers and dc/dc converters, to set the stage for an examination of what the future might bring. By studying some of the fundamental aspects of power-supply technology, and understanding where the applications being powered are headed, we speculate on what advances are needed and delve into how component technologies must develop in the future. Then, based on the demanding needs of powering lower-voltage, higher-current and faster electronics in the future, we offer a power-supply technology roadmap. Our vision is for a future where the necessary advances come by means of much stronger partnerships between power-supply manufacturers, their customers and component suppliers.**

I. INTRODUCTION

The stunning performance advances seen in today's electronics, of which the microprocessor is an excellent example, raises the question whether power supplies will ever achieve similar gains. If power density followed a curve similar to the often-cited Moore's Law, and using the introduction of the IBM Personal Computer in 1981 as the base, today's 250W ac/dc power supply would be enclosed in a box with dimensions of 1"×1"×0.3". And, if cost reductions were achieved at a rate seen with the dynamic RAM industry, this power supply would cost a tenth of a cent! Although significant improvements have been realized, clearly we have not even come close to attaining these performance levels. On first examining these statements, a relevant question is whether this is even a meaningful comparison – comparing transistor density on an IC to power supply density, or cost per bit of memory to dollars per W. It might be more pertinent just to ask why power-supply technology has not made more dramatic gains. Perhaps the most important question of all is, how can the rate of future power-supply technology improvements be accelerated? This paper will try to assess the future by addressing these questions.

We start by examining the fundamental functions performed by a power supply today as shown in the block diagram of Fig. 1. Input power conditioning allows the power supply to present a resistor-like unity-power-factor appearance to the AC utility source, protects the power supply and loads from spikes and surges in the AC line, and keeps EMI generated in the load and the power supply from polluting the AC grid. Since input power from the line is drawn at a frequency of 50 or 60 Hz, and most electronic loads are DC, significant amount of energy-storage capability is also needed in this stage to smooth out the energy flow from the periodically-varying AC input to the smooth DC output. The intermediate power conversion and isolation block steps down the voltage level from the hundreds of volts at the AC input to either an intermediate level such as 48V, or to load voltage levels like 5V and 3.3V. In some applications, energy reserve in the form of batteries is also provided; this is often done at 48V, but can also be provided at lower or higher voltages. The load conditioning function encompasses filtering of the DC voltage, regulation, especially against rapidly varying load transients, and sometimes step down or step up to multiple load voltages from a single intermediate distribution voltage.

II. POWERING ARCHITECTURES

Although today's power supplies perform the same basic functions shown in Fig. 1, as those from two or three decades ago, the basic architecture for powering has evolved towards a distributed approach. Figure 2 shows the development of powering architectures to support telecom and computing over the past thirty years. Initially, most electronic equipment was powered using a centralized power supply located in the cabinet, often the bottom portion. This multi-output supply was used to power different sections of the electronics by using copper cables or bus-bars to carry the currents at different powering voltages needed by the loads. The first

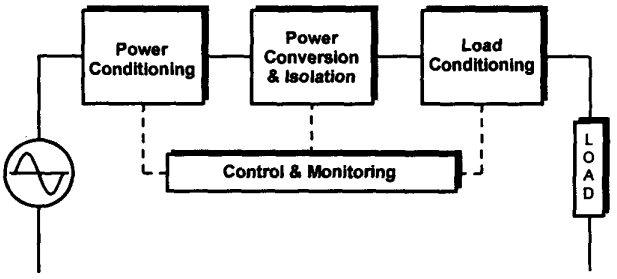

Fig. 1. A simplified block diagram showing power system architecture and functions.

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move towards a distributed architecture occurred in the telecommunications industry [1,2], where the functions of input power conditioning, power conversion and isolation, and load conditioning started to separate both physically and logically. Since 48V had traditionally been used to power telephone exchanges, the next logical step was to provide an intermediate 48V bus that was directly tied to the batteries to provide a source of backup power when AC was lost. In this approach, 48V was delivered to a rack of equipment and multi-output dc/dc converters were used in each shelf to create the different voltages needed by the loads. The next step was to locate dc/dc converters on each load card. This was initially driven by the need to provide fault isolation in telecommunications equipment, primarily for transmission applications. By locating power conversion 'on-board', the failure of a power converter would only cause the loss of service of a card and not the whole shelf. Other advantages soon became apparent, such as lower distribution losses from distributing 48V, and flexibility to accommodate different voltages for a particular application or when newer semiconductor technologies became available.

Today, we are in the middle of a strong migration to distributed architectures for a variety of applications. For total load power levels above a few hundred watts, the move to lower powering voltages of 3.3 V and below for logic ICs has increased the currents to levels where the distribution of these low voltages becomes difficult and expensive. The continuing increase of the speed with which products are brought to market has also made the advantages of distributed architectures even clearer, with the use of standard modules that can accommodate continuing power requirement changes and growth. In addition to these advantages, the distributed architecture has also allowed each module to be optimized for the attributes that are important in the particular application. For example, ac/dc converters have continually been upgraded to improve availability through N+1 redundancy and they have enhanced the interface to the AC utility through active power factor correction. On the other hand, dc/dc converters have moved towards much higher densities and lower profile to accommodate the requirements for placing them on-board, and more recently they have provided greatly improved transient response to meet the needs of fast switching loads. The latest trend in distributed powering architectures is to use a special dc/dc converter dedicated to a single load. This converter, called a POL (point-of-load) converter, is today being used for powering loads with tight regulation requirements such as high-performance microprocessors and power amplifiers in wireless base stations.

The question of how powering architectures will evolve over the next ten to fifteen years depends very much on what power-supply attributes become important, which in turn is highly dependent on how the applications being powered change. Future trends in powering electronic loads can be examined by looking at the technology roadmaps published by the Semiconductor Industry Association (SIA). As shown

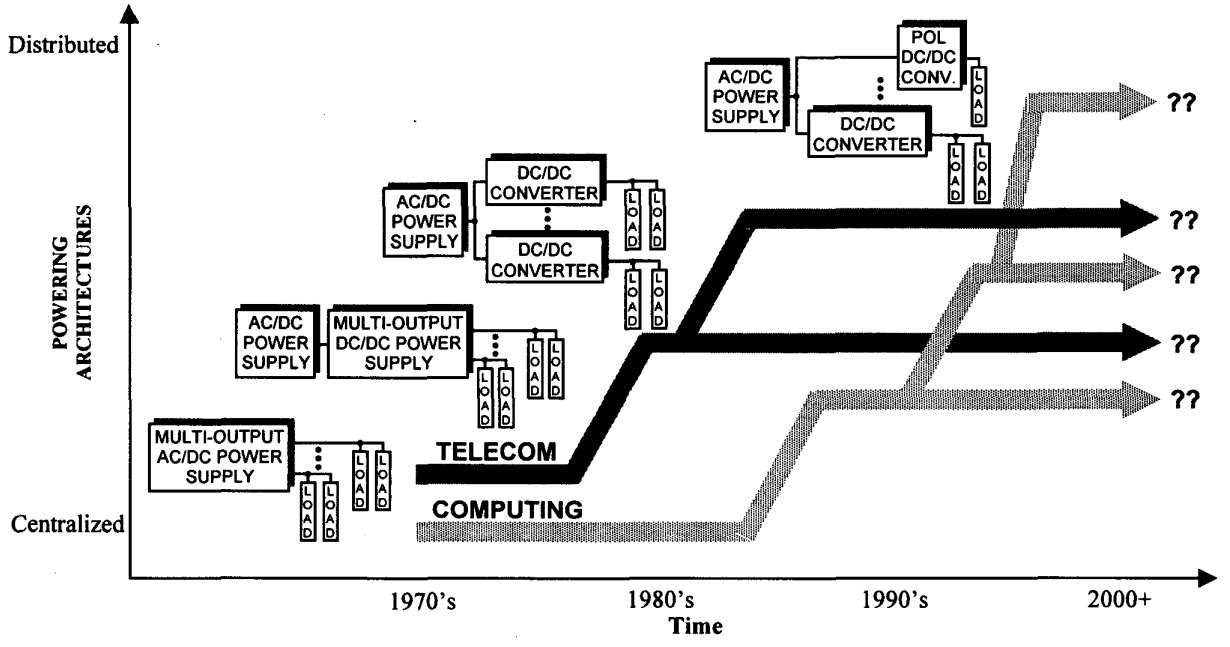

Fig. 2. Evolution of powering architectures to support the growth of computing and telecom.

in Fig. 3, by 2014, switching frequencies are expected to increase towards 10 GHz, powering voltages are going to get lower and decrease towards 0.5 V, while simultaneously the current levels increase. Looking at the past few years, as current levels have increased, the rate of change of current (di/dt) has also increased along with much larger current change amplitudes (ΔI). At the same time, powering voltage levels have gone down and the allowable changes in powering voltage (ΔV bands) in the presence of transient loads also have gone down. In essence, as powering voltages become lower and currents higher, transient response becomes increasingly important. Today, there is a distinct correlation between the ability to keep powering voltage within tighter bands and the maximum clock frequency at which a load such as a microprocessor is capable of reliably operating at. In industry parlance, this is succinctly stated as "better transient response improves bin splits," where bin splits are the proportion of devices such as a microprocessor from a batch of wafers capable of reliably operating at a particular clock frequency.

The higher currents predicted in the future also makes reducing distribution losses important, so locating the load-conditioning converter closer to the load becomes highly desirable. In addition to reducing distribution losses by decreasing resistance, closer location of the power converter

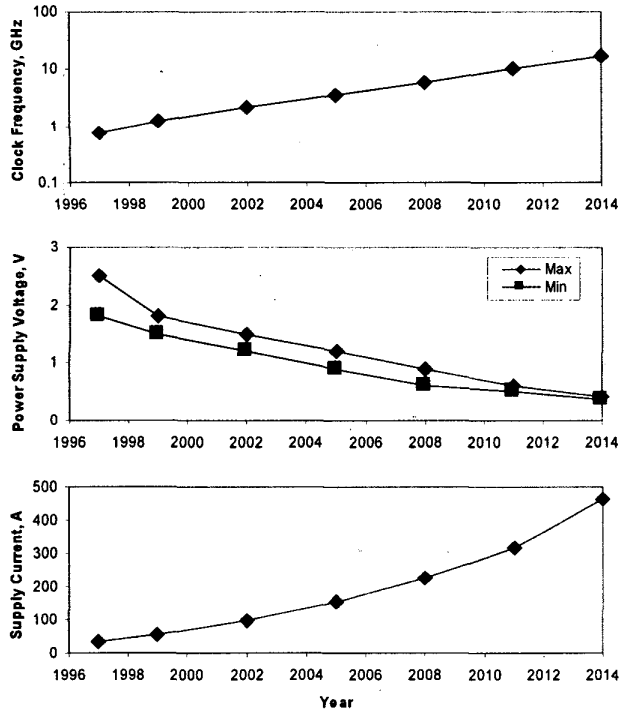

Fig. 3 Future technology projections from the International Technology Roadmap for Semiconductors.

can also reduce the inductance in the path from the converter output to the load. Lower inductance can improve the faster transient response of power converters, and the number of bypass capacitors that are used to buffer the load transients from the power converter can be reduced, freeing up valuable board space and reducing overall cost.

Other attributes that are likely to remain important in the future are cost (constantly get lower), time to market (faster), reliability (higher) and reuse/flexibility (greater). The attribute that is less obvious is density, which has recently become an important measure within the power supply industry of advertising a converter's capabilities. As will be discussed in the next section, density is also tied to efficiency. The question remains however as to how important density really is. To answer this, we examine the importance of power-supply size in the overall system.

III. Importance Of Size And Switching Frequency

The discussion of power-supply density (or size) is begun by realizing that the two different subsystems in a distributed power architecture, the ac/dc and dc/dc sections, have different characteristics and required attributes. First, we focus on the ac/dc section. Is size a major attribute here? Historically it has not been, because beyond cost savings from size reductions leading to more space available for the rest of the system, and some material savings leading to lower costs, there has not been a major driver to achieve higher densities in ac/dc power converters. Going forward, the need for energy storage to handle the periodically varying 50 Hz or 60 Hz input is unlikely to go away. Similarly, the regulatory imposed functions of EMI suppression and safety isolation are also likely to remain. All these factors combine to limit the ultimate size reductions that can be achieved. However, simply by packing components tighter and going to higher levels of component integration, there are still plenty of opportunities for reducing size, at least by a factor of three to five times over today's typical ac/dc converter. And, efficiency improvements and packaging designed for optimized cooling, can reduce the size of the cooling components needed, possibly by an additional factor of two or three.

On the other hand, in the dc/dc subsystem, size has become much more important as power converters have been increasingly located closer to the load. The initial thrust towards smaller size was in reducing the height of board-mounted converters in order to accommodate lower board-to-board pitch and achieve denser packaging at the overall system level. More recently, there has also been interest in reducing the footprint of these converters as well in order to allow increased functionality on each board. The question is whether there is an incentive to push further size reductions in

tomorrow's dc/dc converters. The high current, rapidly changing loads demanded by the microprocessors of today and the future, dictate that power converters get placed increasingly closer to the load to reduce drops due to interconnect resistance and inductance. One speculative scenario is that future powering of microprocessors might involve power converters located next to the die within the microprocessor package, on top of the microprocessor package or underneath the board where the processor is attached. The goal of all these scenarios is to further reduce the interconnect inductance, and potentially reduce the number of processor pins dedicated to power.

On the premise that future dc/dc converters will need to be much smaller, we now move on to examine what the constraints on size are. Since both the input and outputs are DC, there is no intrinsic need for bulky energy-storage devices to handle a low-frequency input like in the ac/dc converter case. Fundamentally, the total size of a power converter is constrained by that of the electrical components and the packaging needed to perform the cooling function. The packaging size is related to efficiency, the higher the efficiency the smaller the size possible. Energy-storage and transfer components such as inductors, capacitors and transformers on the other hand, scale down in size as the switching frequency is increased. The basis for this is that as switching frequency goes up, the element values (inductance and capacitance) needed to provide a particular level of filtering or energy storage are reduced. Prior published work [3] shows that in a flyback converter, reactor mass is roughly proportional to $f^{3/4}$, where f is the switching frequency. However, as [3,4] and others point out, overall reductions in size do not always follow an increase in switching frequency. This is because with increased switching frequencies, the losses in both active and passive components go up, sometimes faster than the frequency itself goes up. The overall size then becomes limited by thermal considerations, and eventually, increases in switching frequency increase losses to the extent that overall size actually goes up to handle the dissipation of the additional loss.

To estimate a lower limit of converter size, we can assume that the same cooling technology used to remove heat from the load will also be used for the power converter. Under this scenario, the size of the power converter is related to the size of the load by the scaling factor $(1-\eta)/\eta$, where η is the efficiency of the power converter. As an example, a power converter with an efficiency of 90%, when embedded in a microprocessor package should from thermal considerations alone, be $(1-\eta)$ or 10% of the total package size. Today, these thermally-imposed basic limits on converter size are far from being reached.

Figure 4 shows a progression of increases in switching frequency over the last four decades. One remarkable fact can be gleaned from examining this figure - each major increase in frequency is driven by improvements in switching devices. The improvement in switching frequency from the 50/60 Hz range to the above-audible range was driven by improved silicon bipolar transistors that enabled faster switching at reasonably high efficiencies. Again, the availability of power MOSFETs in the early 80's pushed switching frequencies to the hundreds of kHz. Soft-switching circuits that take advantage of parasitic capacitances present in MOSFETs have succeeded in switching frequencies pushing the MHz threshold, but the majority of power supplies operate in the 50 kHz to 1 MHz range today. While semiconductor devices have led the push toward higher switching frequencies, improvements in circuits, packaging and magnetic and capacitive components have also kept up, generally following the switching technology changes brought about by new switching devices.

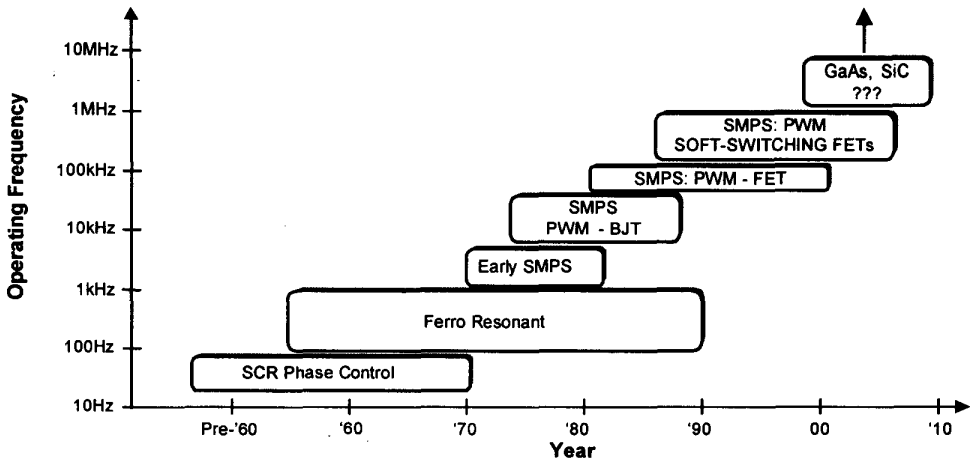

Fig. 4. Plot showing frequencies of different power-supply technologies used in power conversion vs. time of use.

Since switching frequency can be such a dominant driver of power-supply size, an obvious question is why during the decade when microprocessors have pushed operating frequencies from a few MHz towards 1 GHz, power-supply switching frequency has stalled around 1 MHz. To answer this, we examine one significant attribute in comparing power supplies to microprocessors, the energy consumed or dissipated in a single transistor switching cycle. This parameter for microprocessors has gone down dramatically. Since the function of a switching transistor in the microprocessor, is information processing, it is perfectly acceptable to reduce operating voltage and size of the device. In fact, microprocessors have made use of switching dissipation decreasing as the square of the voltage to increase the switching frequency and number of devices per package. In power supplies however, primary-side switching devices today see pretty much about the same current and voltage levels seen two decades ago, and at most a three-to-one reduction for secondary-side switches as logic levels have decreased from 5 V to 2 V and below. This need for power switching devices to handle about the same power levels, coupled with relatively modest improvements in switching devices and the circuits utilizing them, has meant that switching loss per cycle has only decreased moderately, leading to higher losses as the switching frequency is increased. Clearly then, switching devices in the microprocessor and in power supplies perform different functions; in one it is perfectly fine, in fact desirable, to reduce switching power levels, in the other switching power levels cannot be reduced. A clear conclusion is that switching frequency increases to drive major new reductions in power supply density, will not come about without semiconductor device and/or circuits that substantially reduce switching loss per cycle while switching at approximately the same power levels.

To examine how switching frequency in power converters can be pushed higher, we start by examining some published examples of work over the last two decades that discuss switching frequencies of a few MHz and beyond. As early as 1971, driven by the need to reduce weight in dc/dc converters for applications in spacecraft, researchers were looking at conversion frequencies of above a MHz [5]. Later efforts were focused on class-E resonant converters, and a paper from 1983 [6], mentions operation at 14 MHz and as high as 123 MHz with 77% operating efficiency at an output power of 210 mW! Efforts to operate in the 2-20 MHz range intensified in the mid to late 80's [7-10], with the focus still being on resonant converters to reduce switching losses. In these early efforts, the primary focus was on reducing losses in the switch, with magnetics for the converters being a secondary focus, both in terms of suitable core materials and winding structures. More recently, the rapid escalation in current requirements and load transient response characteristics of microprocessors, has pushed the frequency of power-converter operation. Today, many commercially-available non-isolated converters (called VRMs) switch in the few MHz range, with most of them utilizing synchronous rectification to achieve high efficiency at low output voltages. Note that today, the driver for higher frequencies is not size but transient response, and in the VRM application, compromise of efficiency seems to be acceptable if transient response is improved. Beyond this specific application domain, power conversion in the MHz range has not been commercially successful.

To understand the reasons why switching frequencies have stalled, we start by taking a detailed look at the loss mechanisms in today's MOSFET switches. Conduction loss is proportional to the on-resistance and does not change with switching frequency. The frequency-dependent losses can be split into gate drive losses, transition losses associated with switching when both voltage and current are changing and energy losses linked to the drain-to-source capacitance that is discharged every cycle. Among these, the use of soft-switching techniques can virtually eliminate the losses associated with the drain-to-source capacitance on primary-side circuits in isolated dc/dc converters, while these losses are typically small for the synchronous rectifier. The energy associated with charging and discharging the gate capacitance can also be recovered using regenerative gate drives, but the relatively high value of gate resistances and capacitances of today's MOSFETs limits this approach.

Figure 5 shows simplified versions of some key waveforms associated with the synchronous rectifier circuit in an isolated converter [11], an application expected to become increasingly important for the future with the move to lower powering voltages. The key to reducing secondary-side switching losses is lowering the energy required to change the state of the switch, and shortening the duration of the switching transitions, determined in large part by the RC time constant of the gate. Reducing the gate resistance improves this time constant, while reducing the gate capacitance improves both factors. Precise control of the switching instants of a MOSFET are critical to reducing transition losses during switching. Hence, it can be seen that gate losses and transition losses can both be reduced through smaller gate resistances and capacitances. This is because regenerative gate drives can then be profitably employed to reduce gate drive losses, while allowing more precise timing of the switching transitions. Thus, required characteristics for future switches are smaller gate resistances and capacitances, and faster switching characteristics.

Once suitable switches are available, the next limitation in going to higher switching frequencies is the magnetics in the circuit. Since switching frequency stalled in the few-hundred kHz range, magnetic core manufacturers seem to have

focused their advanced development efforts on developing core materials with reduced loss in this frequency range. Ferrites appear to have reached maturity in terms of higher-frequency operation at reasonable loss levels. There are no clear indications of what new materials will likely be applicable at frequencies of 10 MHz and beyond, though permalloy and other materials in thin-film form appear to be promising. Another area of concern in magnetic components when going to higher frequencies is the winding, especially in isolated converters where spacings between windings and the core are needed to maintain isolation levels. As frequency is increased and size of the magnetic component reduced, the useful space available for windings goes down since safety spacings must remain constant. This problem is expected to become worse with the movement towards lower output voltage, higher-current outputs.

In comparison to the switches and the magnetics, capacitor technology has already advanced to be suitable for frequencies of 10 MHz and beyond. This has primarily been stimulated by the improvements in ceramic capacitors with high capacitance per unit volume and ultra-low ESL (equivalent series inductance). There have also been steady improvements in tantalum and electrolytic capacitors both in energy storage density and lower ESRs (equivalent series resistance). Other component technologies generally have been driven by other applications to become capable of high-frequency operation. Additional levels of integration will be needed to keep up with improvements in the switches and energy-storage elements in the push toward higher frequencies. To achieve size reductions as frequencies go up, packaging technologies such as flip chip or chip-scale packaging that facilitate low loss and reduced interconnect impedances, will be need to be used. Much better thermal management will also be required, since if efficiencies remain the same, a greater amount of heat will need to be removed through smaller surface areas.

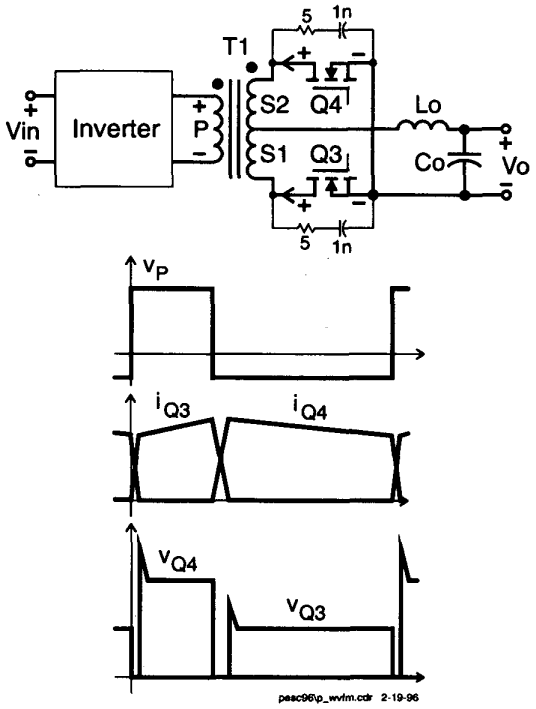

Fig. 5. Schematic diagram and waveforms of a typical synchronous rectifier based isolated dc/dc converter.

IV. Cost Considerations

Cost has and will continue to be a power supply attribute that is always of interest to customers. If we look at why power supply cost has not fallen more rapidly, several reasons are apparent. One is that size reductions have not been achieved because of operating frequency stalling, so that the amount of material being used in the components has not been greatly reduced. In fact, sometimes more material is used to achieve higher efficiencies. The second reason is that there have been few technology breakthroughs to drive component costs down. The reason for this is primarily economic and driven by market factors. Figure 6 shows recent data on X86 microprocessor pricing vs. operating frequency. At any given time, different speed grades of microprocessors are available in the marketplace with different price levels. As newer, faster microprocessors are introduced, the older ones suffer a rapid price decline. Since customers associate computer performance with microprocessor clock speed, at a given time the faster grades always have higher prices. However, as seen in Fig. 6, the slope of the price vs. speed curve increases rapidly when approaching the leading edge of performance. In essence, the market is willing to pay a disproportionately high premium for performance. This market factor today strongly dominates microprocessor technology development and provides a powerful economic incentive to push microprocessor frequencies higher and higher. Similar market characteristics

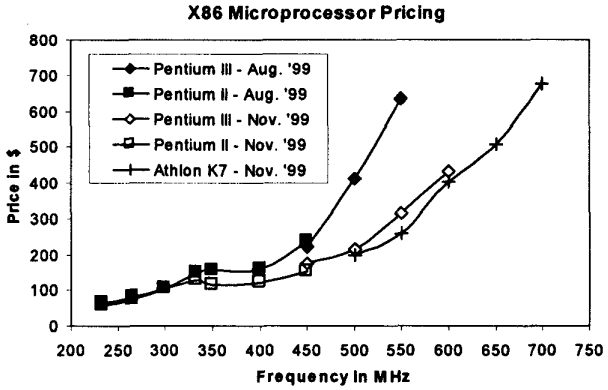

Fig. 6 X86 microprocessor pricing vs. frequency.

can be seen in other leading-edge electronic products.

What about power supplies? Customers appear unwilling to pay a similar price premium for power-supply density. Hence the economic incentive to push for dramatically higher power-supply densities does not seem to be there today. If it were, power-supply manufacturers would have significant incentives to in turn push power-supply component manufacturers. For the future, small size of dc/dc converters may turn out to be a key enabler in powering high-performance loads, and there will then be an economic incentive to pay for the needed technology improvements. In this scenario, it could be very profitable for a switch manufacturer to create a switch with lower gate capacitance and faster transition times.

V. Power Supplies Of The Future

To help visualize the powering scenario of the future, we consider what would be needed to power a high-performance IC in 2010. From the roadmaps in Fig. 3, the powering voltage is expected to be around 0.5V at a maximum current of about 250A. At these current levels, a non-isolated converter would still have fairly hefty input currents. Hence, the power converter is likely to be an isolated converter with an input voltage of 48 V, or perhaps lower at 12 V. The difficulty of distributing such a large current like 250A would probably lead to distributed power converters within the chip package. Figure 7 shows a hypothetical IC package with distributed power converters around the periphery. These converters are estimated to be about 0.1"×0.4"×1", corresponding to a power density of 1000W/in^3. The use of multiple converters provides two advantages. First, power can be delivered to different edges of the die, removing the need to distribute power across the die. Secondly, the level of power and current processed by a single converter is reduced, allowing size reductions to accommodate it in the processor package.

The need for future dramatic reductions in size enabled by an increase in operating frequency, while maintaining efficiency at the 90% or greater level for an output of 0.5 V, leads to the important question of how these challenging goals can be achieved. The key technology improvements needed are shown in Fig. 8, and can be summarized as follows:

- Better (faster) semiconductor devices with smaller gate resistances and capacitances and faster switching. Lower on-resistances will also be needed to contribute to lower overall dissipation. Particularly important are devices which are optimized for synchronous rectification with very-low-voltage outputs; these could be devices with lower drain-to-source breakdown voltages of 5 to 10 V, and proportionately lower gate drive voltages. Figure 8 shows that low-voltage switches for synchronous-rectifier applications need to go down in on-resistance from

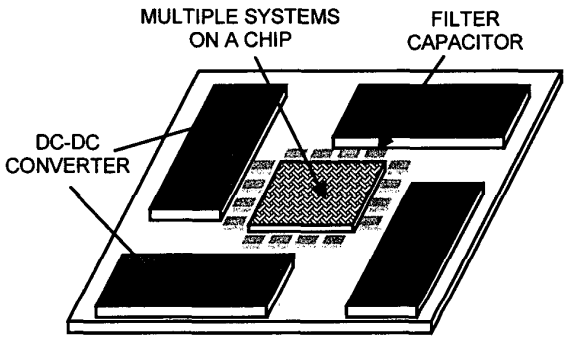

Fig. 7. Diagram showing potential future microprocessor + power converter arrangement.

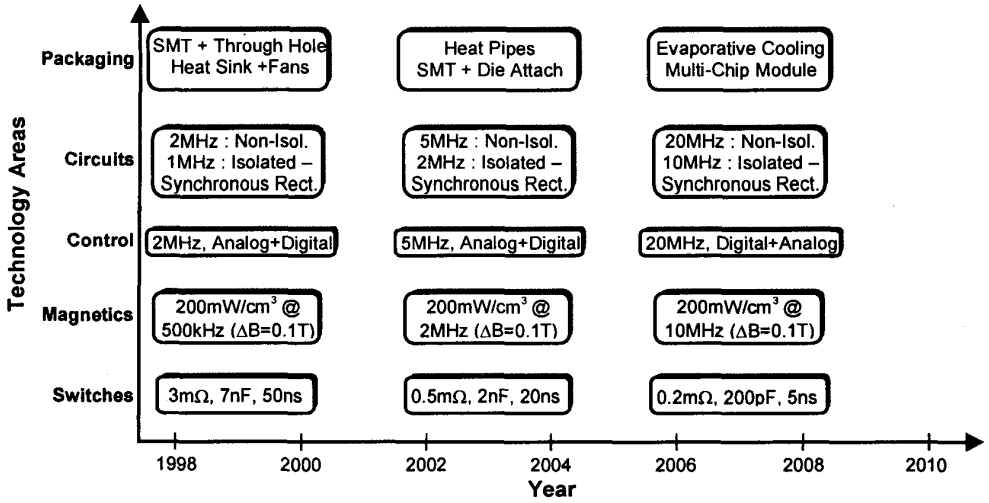

Fig. 8. Technology developments needed to reduce size by increasing operating frequency.

today's 3 mΩ with 7 nF of gate capacitance and switching speeds of ~50 ns, to an on-resistance of about 0.2 mΩ, with gate capacitance of 200 pF and switching speeds of ~5 ns.

- Improved magnetic materials with reduced core loss in the 10 MHz to 50 MHz range are also needed. Such materials would need to be made with inexpensive fabrication methods to handle power levels of 20 W and more, in order to develop isolated power converters capable of powering future microprocessors and other high-current loads. Figure 8 indicates one measure of benchmarking core loss; such losses would have to go from 200 mW/cu. in. today at 500 kHz, to 200 mW/cu. in. at 10 MHz, both for a peak-to-peak flux density of 0.1 T.
- Faster control circuitry that can provide precise timing for driving synchronous rectifiers and other control functions along with integrated drivers suitable for 10 MHz+ operation are also needed. Control techniques for squeezing better transient response at a given switching frequency through the use of nonlinear control techniques and/or digital control are areas with good research potential.
- Circuit innovations are needed to push frequencies higher and size smaller. In particular, isolated converter circuit topologies with synchronous rectifiers that enable operation at frequencies of 1 MHz and above, while keeping switching losses low.
- Better packaging along with integration and easy assembly of multiple components, especially those approaches which improve thermal management are also needed.

To achieve the technology improvements discussed, what is required is a much stronger partnership between power supply manufacturers, customers and vendors. Following the message discussed in [12], power-supply manufacturers need to treat their vendors as an intimate and integral part of our business, and request the same relationship with their customers as well. Successfully powering the applications of the next millennium will need many more close cooperative relationships than we have had in the past, and through organizations like the IEEE and the PSMA we can and should foster and nurture such partnerships within our industry.

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