On a Future for Power Electronics

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(Invited Paper)

***Abstract*— This paper presents a historical and philosophical perspective on a possible future for power electronics. Technologies have specific life cycles that are driven by internal innovation, subsequently reaching maturity. Power electronics appears to be a much more complex case, functioning as an enabling technology spanning an enormous range of power levels, functions and applications. Power electronics is also divided into many constituent technologies. Till now, the development of power electronics has been driven chiefly by internal semiconductor technology and converter circuit technology, approaching maturity in its internally set metrics, such as efficiency. This paper examines critically the fundamental functions found in electronic energy processing, the constituent technologies comprising power electronics, and the power electronics technology space in light of the internal driving philosophy of power electronics and its historical development. It is finally concluded that, although approaching the limits of its internal metrics indicates internal maturity, the external constituent technologies of packaging, manufacturing, electromagnetic and physical impact, and converter control technology still present remarkable opportunities for development. As power electronics is an enabling technology, its development, together with internal developments, such as wide bandgap semiconductors, will be driven externally by applications in the future.**

***Index Terms*— Future of power electronics.**

I. INTRODUCTION

WHEN attempting to construct a possible future for power electronics, different approaches are possible. In this paper, we take a historical and philosophical perspective from the outside. This paper first shows the motivations for this approach in Section II, looks at the historical development in Section III, and examines the present state of the art in power electronics in Section IV. To facilitate this discussion, fundamental internal functions for power electronics are suggested, and the entire field of power electronics technology is divided into a series of interrelated constituent technologies. Section V discusses the examples of emerging applications and technologies in the field of power supplies to illustrate how they are driving the development of the constituent technologies of power electronics. Section VI examines the future driving forces, leading to up to the importance of emerging technologies and applications in driving the envisaged future development of power electronics.

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II. DO WE KNOW WHERE WE ARE HEADING?

A. Lifetime of Technologies

In our technological society, we have come to accept that technologies come and go. It is, however, extremely important to understand why this happens, how this will happen and when this will happen. Entire industries can disappear when technologies become obsolete, so it is important that appreciable resources be devoted to understand the process of obsolescence. Road-mapping the future of a technology cannot be a mere extrapolation. In this case, it will be based on the assumptions derived from the processes that have been fuelling the development of the technology that is the subject of the investigation. Among other things, a road map needs to consider sufficient history and underlying philosophy driving the technology.

A good example of an inability to anticipate immanent disruptive change in electronic technology is the following. In November 1952, the IRE published a special issue of its proceedings, the Transistor Issue, containing 48 papers on this new technology. In a foreword, McRae, Vice President of Bell Telephone Laboratories, attempts to foresee what impact transistors will have on the economy [1]. In that very same issue, however, we find a two-page advertisement from a large industry—now long extinct—announcing the start of a great new division for full scale manufacture of vacuum tubes to become the leader in research, development, manufacture, and marketing of electronic tubes [2]. Naturally, this does not illustrate that it is futile to speculate about the future of a technology, but serves as an illustration of what can happen if one relies only on extrapolating the present. In the last 50 years, the rate of technology obsolescence has increased remarkably, hence the importance of the history and philosophy underlying each technology in our approaches to gauge the life history of our technologies has become more essential.

One can certainly identify many reasons contributing to engineers being less aware of the aspects that are underlying their technological specialization, but three important reasons appear to be as follows:

1) The emphasis in our education on technology has always been inward and not outward—and as the extent of technological knowledge explodes, this tendency only intensifies.
2) The growing complexity of technological artifacts, systems and processes implies that large teams are involved in development and application, whereas the individual is increasingly busy with smaller and smaller pieces of the whole and has little influence on—and oversight of—the total technology, its lifetime and impact.

3) Our educational system in engineering/technology appears to have time constants world-wide that exceeds technology lifetimes by many multiples. In many subjects, students are at present still taught the same material as was taught 20 years ago. How much is invested in what they should know 20 years from now?

B. Power Electronics Technology

Power electronics has not escaped from these tendencies, and it is incumbent on us to examine them critically at this stage of the life cycle of our field of expertise. It has been suggested that power electronics is a mature field with limited further scope [3], while recent work has explored in detail the dynamics of power electronics as they approach their limits in terms of technical metrics [4]. These are valuable studies, and we will return to these thoughts later. However, it is necessary to explore where we are going in power electronics against the entire background of the historical and philosophical perspective of this technology, and not to concentrate only on the internal metrics and details of the subject. For example, it has been noted repeatedly that new topologies will not be driving the future development of power electronics [5]–[7]—and indeed history teaches us that the relevant topologies used in industry today are for the larger part older than most of us [8], [9]. Very few new topologies have been adopted, yet our infatuation with new topologies remains. It is an interesting exercise to page through conference proceedings and transactions and read how much work is still devoted to developing these new topologies. Is this a typical reaction of a mature technology that academically reverts into itself by looking only inward? Is the external question of whether this is really relevant in the context of future application suppressed?

C. Road-Mapping Power Electronics

As an attempt to find out where we are heading, road-mapping the different sub-fields within power electronics has been a well-practiced and well-documented activity in our more recent past [4], [10]. From a philosophical point of view, however, internal road-mapping cannot possibly tell us where we are going if the field is becoming mature and nearing the limits of technical achievement. This does not imply that development will stagnate, but rather that further development in aspects not contained within these internal metrics is likely to be driven by external considerations. As an example, a converter with the same efficiency can be packaged by integration in a way that is totally different from traditional packaging, decreasing manufacturing cost and improving form factor that may enable it for a new application. In the future of a mature field, something is going to give, to bend or to disrupt—or new drivers are going to appear. These highly nonlinear events are externally superposed and fall outside an internal frame of reference. An example of a growing external influence is the increasing public awareness that electric energy needs to be saved, and that sustainable electric energy sources need to be introduced. In many programs it is becoming clear that power electronics is the essential technology for achieving this, hence we can expect that this will become a strong external driver in the future, yet we totally lack the capability to quantify the contribution of power electronics [11]. We will return to external drivers in Sections VI-B and C.

III. Notes on the Historical Development of Power Electronics

A. Documented Historical Development

Let us now turn our attention to historical development to see what it teaches us on the underlying philosophy of power electronics. Unfortunately, there is still no work in existence that forms an encyclopaedic reference for the history of electronic energy processing. We have snapshots of the state of power electronics at certain instants in old text books that trace specific historical developments [12]–[14], while studies of certain aspects, such as application to electric machine control [8], [15], or of some historical developments [9], [16], provide some insight into when and where important ideas and technology advances came about. There are two bibliographies that cover the time from 1903 to 1966 [16], [17], while the IEEE have published Special Issues of the Proceedings of the IEEE on aspects of power electronics over the last 50 years in 1967, 1988, 1994, and 2001 [18]–[21]. Collectively, these works [5]–[21] present references to literally thousands of publications, patents, inventions, and applications. This enormous collection of references, when studied chronologically and in detail, will provide the missing encyclopaedic history of power electronics, but such a history still remains to be compiled.

B. Development of a Central Driving Philosophy

We have, however, sufficient information from the fractionally documented history to guide us for the moment. It appears that initially, some characteristics of vacuum tubes were varied to create a continuously variable resistance. Van der Bijl [22] describes the use of thermionic triodes in series or in parallel with the field of dc generators to control the field. The grid was used to operate the tube as an electronically variable resistance. Voorhoeve [23] used diodes for the same purpose and in the same way by changing the heating current and thus the diode's resistance. This use of a time-variable resistance in the circuit was the first step in introducing a nonlinear element to electronically control average power. At that time, all gas discharge tubes that had been in existence since 1903 [16], [17] were in principle uncontrollable, so they could not be used in this way. It was soon apparent that the power level of these methods of using an electronically controllable resistance was severely limited, until Prince [24] came upon the idea to use grid control to switch vacuum triodes and built the first inverter. Langmuir had already invented grid control for gas discharge tubes, but it was not until 1928 that Prince used this as a much improved switch to construct inverters with much higher efficiency. The delay in innovation was caused by the need to first invent the concept of forced commutation to turnoff current [9], [25] in gas discharge devices.

Power electronics had now finally set its course to the philosophy of introducing a switch as a nonlinear element between the electric source and load to control average power [26]. Future generations of power electronics technologies would now be born according to the switching times, losses, size, cost, ruggedness and controllability of power switches [16]–[21]—and these would really take off after the introduction of transistors and thyristors [18]. Thus, the central philosophy driving power electronics for nearly a century came into existence. The observation that advances in power electronic switches will drive this technology has been borne out by so many generations of devices [18]–[21] that it has been elevated to an untouchable tenet for the power electronics roadmap. Yet, it is perhaps time that we heed the example of the vacuum tube advertisement in the Special Issue on Transistors of 1952 [2]. It does not appear that the paradigm of how we control average power between source and load is about to change, as it was in 1952, but the driving philosophy of only advancing the technology of the nonlinear element in the system and the topologies for arranging this element in the system may simply not be interesting any more to the future forces that are starting to drive power electronics from outside.

IV. Present State-of-the-Art in Power Electronics

The present state-of-the-art in power electronics has been characterized as mature [3]. However, when power electronics is characterized as mature, it is important to realize that this refers to how the technology is practiced at present—as it is seen from inside. This maturity consequently only applies to certain of the constituent technologies of power electronics—as will be defined in Section IV-A.

A. Characterizing Power Electronics Technology

1) Fundamental Functions in Power Electronics: In the past it has been customary to refer to the concept converter in terms of an electrical circuit diagram of the connection of power electronic components; i.e., the so-called abstract circuit topology of the converter. This concept of converter is too restrictive to enable either a proper discussion of the present status and trends or the future. In the following sections a much more generalized concept of converter is used.

For our purposes, a converter will be taken as the total of the equipment between source and load that have the objective of the conversion and control of electromagnetic energy flow between an electric source and the load. The power electronic converter has internal fundamental functions that characterize the different aspects of its functioning. These functions, shown in Fig. 1, relate to the propagation, conversion and control of the flow of electromagnetic energy, and are found at all power levels, in all types of converters for all applications:

1) the switching function controls electromagnetic energy flow/average power;
2) the conduction function guides the electromagnetic energy flow through the converter;
3) the electromagnetic energy storage function enables energy continuity when interrupted by the switching function;

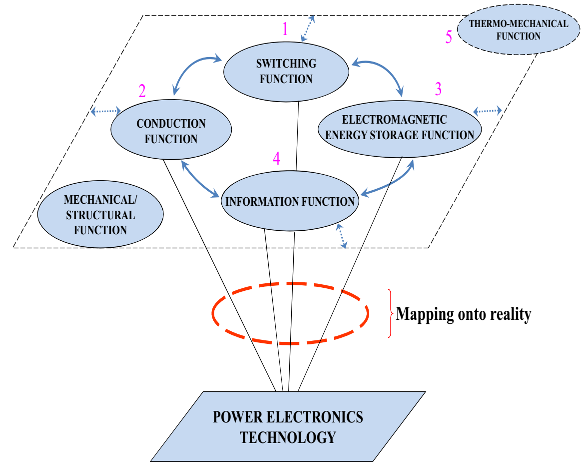


Fig. 1. Internal functions of a power electronic converter.

4) the information function enables the required time interrelationship between the previous three functions to execute the fundamental function of the power electronic converter;
5) the heat exchange function stabilizes the thermal operation of the converter;
6) the mechanical/structural function guarantees the physical stability of the converter.

These internal functions of the converter are intimately interrelated. The way in which these internal functions map onto reality is by a specific type of converter technology. It is the salient characteristics of this technology that have been characterizing power electronics over the past century—and not only the switching function and topologies. The way in which this mapping occurs is constituted by a range of specific subtechnologies—to be termed the constituent technologies.

2) Mapping the Fundamental Functions onto Reality: When the fundamental functions of power electronics are mapped onto reality by any type of technology, a number of constituent technologies can be identified, as shown in Fig. 2, independent of the type of converter, power level, or type of application. These constituent technologies are now identified as:

1) power switch technology (covering device technology, driving, snubbing, and protection technology);
2) power switching network technology (i.e., what is classically termed converter technology, covering the switching technologies, such as hard switching, soft switching, resonant transition switching, and all the topological arrangements);
3) passive component technology (covering magnetic, capacitive, and conductive components);
4) packaging technology (covering materials technology, interconnection technology, layout technology, and mechanical construction technology);
5) electromagnetic environmental impact technology (covering harmonics and network distortion, EMI and EMC);
6) physical environmental impact technology (covering acoustic interaction, physical material interaction i.e., recycling, pollution);

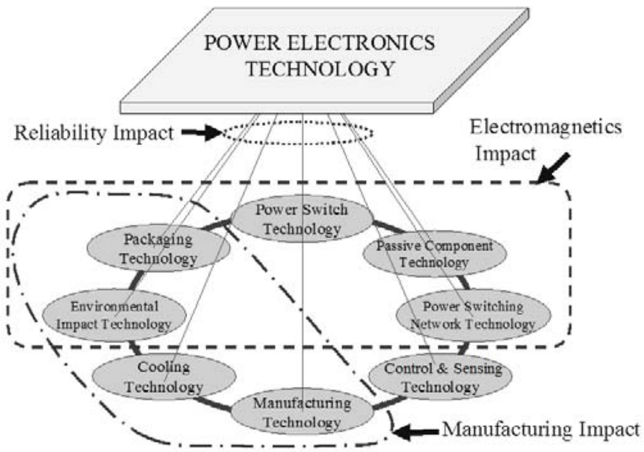


Fig. 2. Interrelationships in power electronics constituent technologies.

7) cooling technology (cooling fluids, circulation, heat extraction and conduction, and heat exchanger construction);
8) manufacturing technology;
9) converter sensing and control technology.

All these constituent technologies are interactively related to each other, contributing to the complex nature of designing, building and operating power electronics. For instance, Fig. 2 also suggests some groupings where electromagnetics or manufacturing has a stronger impact. It is also notable that reliability impacts all these constituent technologies, albeit in varying manner. It is also to be expected that the interactive relationship of these constituent technologies in forming power electronics technology will be dependent on the position in the Power Electronics Technology Space, to be defined next.

B. Power Electronics Technology Space

It is now to define the concept of the Power Electronics Technology Space. This will be an aid in visualizing the enormous range of power electronics technology, as follows (see Fig. 3):

1) *Power:* Power electronics span power levels from below milliwatts to above gigawatts, with the technology for these converters to change over this range. One axis for the technology space is consequently chosen as the power level.
2) *Functions:* Power electronic converters are implemented to interface sources of electric energy with the distribution—source converters. Interfacing the distribution with the loads requires the use of load converters. Electric power is also conditioned in the distribution network, resulting in the family of network converters. The requirements and consequently the technology for each of these three families can be much different, leading to the definition of the second axis as functions.
3) *Application:* On the source side, the load side and during transmission in a network—at the same power level—the environmental conditions and regulatory requirements can be much different, depending on the type of application, so that a third axis is formed by application type.

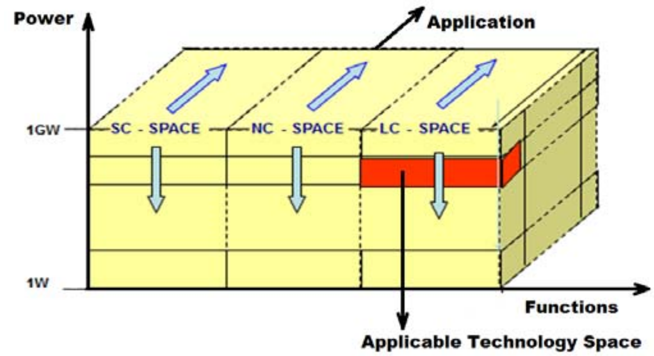


Fig. 3. Technology space for power electronics converters.

A specific power electronics technology can now be defined for an Applicable Technology Space (ATS). This allows us to recognize distinct technologies suitable only for a specific ATS, such as in the voltage regulator module-space (power supply on a chip), uninterruptible power system-technology space, wind power converter space, fuel-cell converter space, and so on. It is therefore, clear that our subsequent discussion of trends has to consider only generic matters applicable throughout this power electronics technology space.

C. Trends in Internal Constituent Technologies

Of the constituent technologies defined above, the power switch technology, power switching network technology, and passive component technology have been termed as internal to power electronics, while the other technologies will be considered as external to power electronics. In keeping with these previous remarks, the constituent technologies that can be considered internal drivers of the technology will be evaluated first.

1) Devices and Power Switch Technology: The power-frequency product of devices [27], [28] has served a good measure to evaluate the progress and status of power electronics. When examining the factors that influence the power-frequency product of devices, the following fundamental relationships emerge regarding the material, the device structure, and the semiconductor device technology:

1) The material properties (bandgap, carrier mobility, doping, and thermal conductivity) influence the breakdown voltage, conductive voltage drop, turn-on and turn-off times, and maximum chip dissipation.
2) The device structure (types and numbers of junctions, 3-D cell structure, and external contacting layout) influence the breakdown voltage, conductive voltage drop, and turn-on and turn-off times.
3) The semiconductor device technology (oxides, types of junction formation and doping) chiefly influence the breakdown voltage and turn-on and turn-off times.

Considering all these influences, it is remarkable that over so many device types and such a large frequency range, the power-frequency product remains approximately constant for a material, such as silicon [27], [28]. As the wide bandgap materials, such as SiC and GaN emerge, they pose new challenges with a potentially significant increase in operating temperature and frequency. Rather, these technologies may be an important enabler for future external drivers (such as new applications, cooling, manufacturing, and so on).

Switching losses have also been on a steady decline with the improvements in device technology, device types, driving, and ruggedness [29]. In particular, the decrease in device losses has been brought about by a continuing decrease in turn-on and turn-off times and drive power. These have reached such a level at present that it is parasitics in packaging/interconnection that is limiting the next generation of improvements (GaN). It has become evident that an approach other than the packaging and interconnection technology that has been developed up to the present will be necessary to take further advantage of any order-of-magnitude device improvements regarding shorter turn-on and turn-off times for new applications, such as is being presented by GaN.

2) Power Switching Network Technology: Power switching network technology has been developing continuously since the beginning of the history of power electronics, and presents a mature field with a vast array of topologies [30]. Large families of dc to dc, dc to ac, ac to dc, and ac to ac power switching networks have been developed [30]–[32]. From the viewpoint of these networks as switching power processors, it is a fundamental consideration that if the network receives electrical power at a given frequency and a given voltage/current level at its input and delivers power at a different frequency at its output, both the input and output will contain unwanted frequencies differing from the original value, and these unwanted frequencies have to be sunk some way or other by the networks connected to the input and output of the converter. The amplitudes of these unwanted components are a function of the following:

1) the internal switching function used (such as PWM);
2) the type of switching technology used (hard switching or soft switching, due to factors, such as different snubbers, resonant, or resonant transition switching) [30], [31];
3) the technology and size of the electromagnetic components, the interconnections, the layout and the parasitics in the switching network.

A large proportion of the work on power electronics technology during the last 25 years has been devoted to characterizing and mastering these reflected frequencies to reduce unwanted interaction between the converter and the supply and the converter and the load. During these developments, the power efficiency of these power electronic switching networks has been advanced to unprecedented levels, in spite of these unwanted generated components. These values of efficiency have consistently reached 90% and above, while values as high as 99% [4] are possible at certain power levels. These efficiencies have been possible due to the high on-off discrimination factor of power semiconductor devices, reaching values of the order of 10^3 for the ratio between the blocking voltage and conduction voltage drop, while the low switching losses in all modern power semiconductor technologies have significantly reduced the total losses [29].

When examining details of the present state-of-the-art in power electronic switching networks, it is evident that a multitude of possibilities exist, which cannot be evaluated in detail here [33]. Generically, converter topologies can be combined by cascading the converters in parallel or in series to form a very large range of switching network structures [20]. The work of the past has been devoted to the analysis and synthesis of these possibilities in great detail, and it is fair to consider them among the most mature constituent technology at present—in spite of the continuing flood of publications.

3) Passive Component Technology: In the development of power electronics technology, passive components have followed rather than driven any developments. As the frequency of operation and the power density have increased, it has become evident that conventional components and their construction techniques need serious attention to reduce parasitics, while sustained magnetic and dielectric materials development should reduce losses due to the ever-increasing current and voltage slew rates. However, material limitations have not allowed the same dramatic increase as was experienced in the switches, so that in many cases passive components present an internal limitation.

In addition, passive components need to be electromagnetically designed for specific packaging and interconnection configurations—and not in isolation of the way they are to be used in converters. This trend can be seen at present for power surface mount components, but not at higher power levels.

In summary, no dramatic improvement in passive component technology has been forthcoming in the traditional way of packaging power electronic converters. This technology can consequently be considered mature, as far as its development is being driven by traditional power electronics packaging.

D. Trends in External Constituent Technologies

Packaging, cooling, manufacturing, environmental impact, and converter control technology may be considered to be the external constituent technologies. These external constituent technologies form the bridge between the mature internal constituent technologies and the applications. In 1991, a series of workshops on the future of power electronics was initiated, with technical sponsorship by the Power Electronics and Industry Applications Societies [34], [35]. From the discussions at these workshops it was always clear that the external constituent technologies of power electronics are all intimately dependent on the ATS being considered, i.e., the power level and function of the converter and application type—see Fig. 3. These interrelationships differ greatly between specific positions in the entire power electronics technology space. In contrast to the mature internal constituent technologies, these five technologies are in no way mature in the way they can be applied in the future of power electronics—as the cited discussions have underlined.

1) Packaging Technology, Manufacturing Technology, and Cooling Technology: At the lowest power levels, monolithic and hybrid integration has become the packaging technology of choice, while the power semiconductor modules that cover the range up to high voltages still rely heavily internally on the discrete interconnection approach that has been followed throughout the history of power electronics. The construction of total converter systems has been changed drastically by the use of these modules in terms of packaging, manufacturing and cooling, as dictated by the specific position of the application in the ATS—see Fig. 3. The discrete interconnection approach and discrete components outside the module have remained in place, however. Recent case studies have clearly illustrated the possibilities of extending hybrid integration concepts to a system-in-a-module approach, changing the interplay between packaging, manufacturing, and cooling to a new paradigm [36], [37].

2) Electromagnetic Environmental Impact Technology: Electromagnetic emissions from power electronics has already become a very important issue due in large measure to regulations, standards and recommendations that have come into effect internationally, as well as the fact that the total power being processed by these converters is increasing rapidly. This leads to strong emissions [34], [38]. The solution to this problem is critically dependent on the application, and presents enormous challenges and opportunities closely related to components, packaging, manufacturing, and cooling. A case in point is the proliferation of electromagnetic interference (EMI)-generating converters in smart homes and smart grids at present, presenting remarkable opportunities for technology development.

3) Physical Environmental Impact Technology: The situation with respect to materials and process impact on the environment might develop analogously, as regulations are already in place in several countries for the electronics and electrical industry [39], [40]. It has to be kept in mind that power electronics contain large volumes of material, and consequently recycling strategies that include manufacturers taking back obsolete equipment will have a major impact on new developments and cost. Additionally, in this regard there is no quick fix analogous to the EMI filters at the input of a converter, but instead it will have to be solved during development, design, packaging, and manufacturing, which again presents enormous opportunities. Awareness of the energy embodied in a power electronic converter system (for manufacturing, recycling, and operation) has only recently emerged [11] and presents impressive technology development opportunities for the future.

4) Converter Control and Sensor Technology: The lower-level control functions of the power electronic switching networks (current loops, voltage loops, and PWM) have been comprehensively addressed in the last 50 years in a classical sense [41]–[43], and may well be considered mature [3]. The energy/power management at the system level remains a challenge, especially for portable handheld electronic equipment, such as smart phones, tablets, laptop computers, and many other consumer electronics.

The application of artificially intelligent techniques to the control of these systems (fuzzy logic, artificial neural networks, and genetic algorithms) [43], [44] has not always clearly demonstrated the advantages of the new approach in comparison with the classical approach. However, if the inherent adaptive nature of these approaches is considered, totally new concepts become possible. Furthermore, in the application of these techniques to more difficult problems, such as self-commissioning and adaptive systems, the advantages for future intelligent converters become abundantly clear. These important advances can again only be driven externally by emerging applications—and not from within.

V. Examples of Emerging Applications and Technologies

In this section, emerging technologies in the ATS for power supplies is considered (Fig. 3) to illustrate their influence.

A. U.S. Power Supplies Industry

Power electronics products, to date, are essentially custom-designed. With a long design cycle, today's power electronics equipment is designed and manufactured using non-standard parts. Thus, manufacturing processes are labor-intensive, resulting in high cost and poor reliability. This practice has significantly weakened the U.S. power electronics industry in recent years. In the 1980s, power electronics was considered to be a core enabling technology for all of the major corporations in the U.S. In the 1990s, the major corporations adopted an outsourcing strategy and spun off their power electronics divisions. What had been a captive market was transformed into a merchant market. Fewer resources were available to devote to technical advancements in power electronics. Therefore, innovative solutions were scarce, and products became commoditized and cost-driven. The result was the increased mass migration of manufacturing to countries with low labor costs. The problem is further compounded by the more recent trend of outsourcing engineering to India and Asian countries, especially China. Today, most of the industry is focused on the bottom line and spends little on R and D, and of this most is spent on development rather than on research.

B. Trend for Distributed Power Systems

With ever-increasing current consumption (> 100 A) and clock frequency (> GHz), today's microprocessors are operating at very low voltages (1 V or less) and continuously switching between the sleep-mode and wake-up mode at frequencies of up to several MHz to conserve energy. Lee [45] has proposed a multiphase voltage regulator (VR) module for new generations of Intel Pentium microprocessors (Fig. 4).

This multiphase VR technology is simple and is easily scalable to meet ever-increasing current consumption, clock rates, and stringent voltage regulation requirements. With the ability to shed phases according to the load demand, it demonstrates superior efficiency at light load, at which microprocessors operate most of the time. Today, every PC and server microprocessor in the world is powered with this VR. These technologies have been further extended to high-performance graphical processors, server chipset and memory devices, networks, telecommunications, and all forms of mobile electronics. For example, in telecommunication applications, 48 V has been adopted as the low-voltage bus

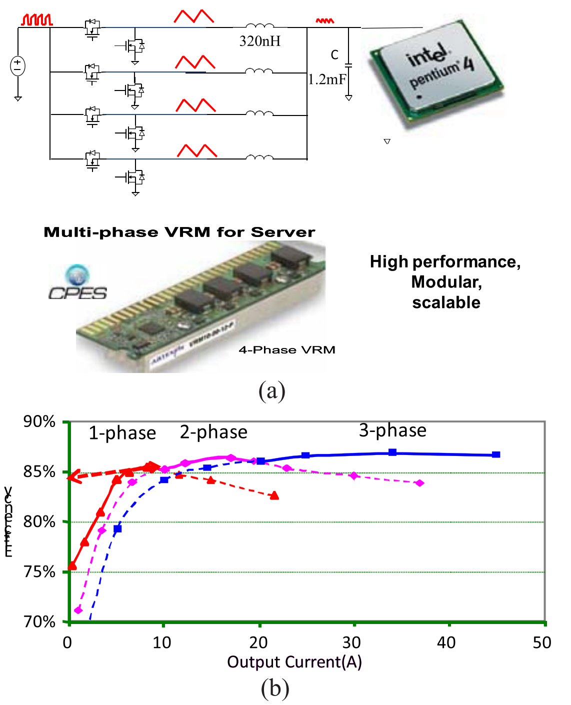


Fig. 4. (a) Multiphase VR for the new generation of microprocessors. (b) Efficiency improvement at light load using phase shedding and burst-mode operation.

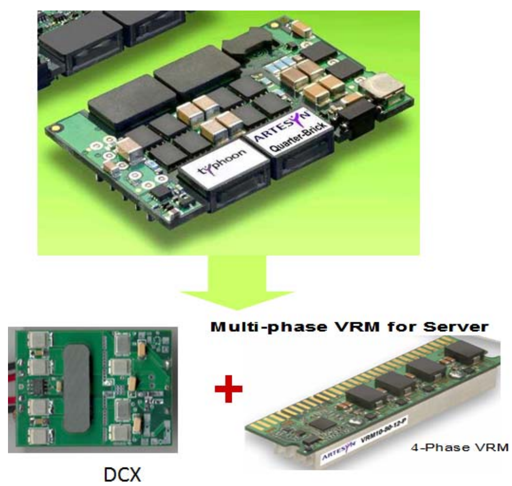


Fig. 5. Dc/dc brick converter is replaced with DCX and POL VR.

for all switch boards. A number of isolated dc/dc converters, often referred to as brick converters, are employed for conversion from 48 V to low-voltage outputs in each switch board. The brick converters demand high power density and high efficiency, and thus are very competitive products and laden with IPs. With the advent of multiphase VRs, these brick products have been quickly converted into a two-stage solution, with a simple dc/dc transformer (DCX) followed by a multiphase VR, as shown in Fig. 5, with demonstrated improvement in efficiency, power density, and even cost.

With the widespread use of distributed point-of-LC, the power architecture has undergone significant changes, from centralized customized power supplies to more distributed

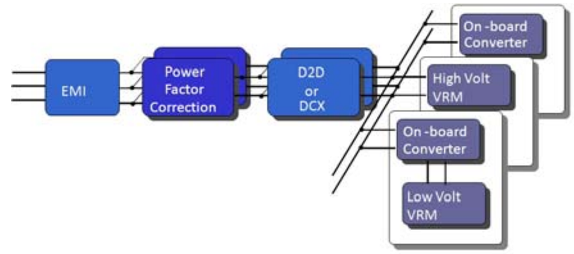


Fig. 6. Distributed power architecture.

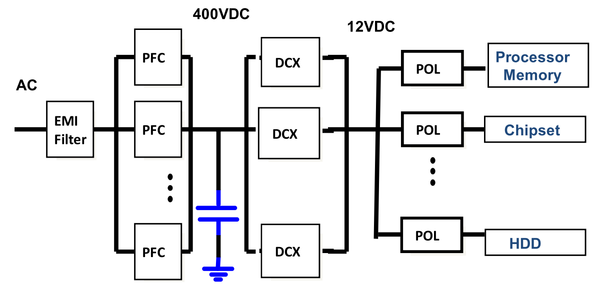


Fig. 7. DPS based on simple building blocks.

power supplies (DPS), as shown in Fig. 6. In this DPS architecture, the modular approach has been adopted for even the front-end power conversion. The DPS architecture offers many benefits, such as modularity, scalability, fault tolerance, improved reliability, serviceability, redundancy, and a reduced time to market.

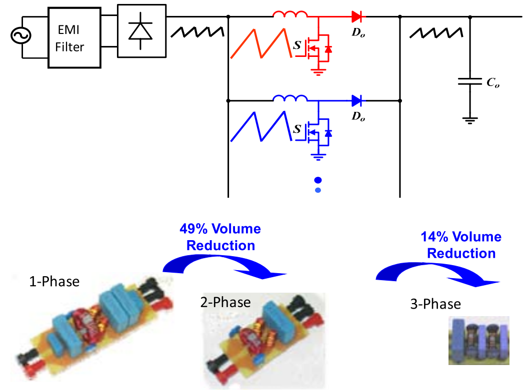
The widespread use of DPS has also opened up the opportunity in the power supply industry to develop a standardized modular approach to power processing instead of the predominantly custom-designed products currently used.

It is envisioned that such distributed power architecture will be further evolved and simplified, ultimately into something like Fig. 7, where any given system can be synthesized by a number of simple building blocks, such as boost PFC, DCX, and buck VRs. This, in turn, will offer the opportunity for a new design paradigm.

Fig. 8 shows that the successful deployment of multiphase VRs can be simply extended to a multiphase boost PFC [46]. Most of the benefits derived from the multiphase VRs are directly applicable to multiphase boost PFCs. In addition, due to input/output current ripple cancellation, there is a significant size reduction of the input filter and output filter capacitor.

DCX can be made very efficient while achieving very high power density, as shown in Fig. 9 [47], [48] for 48 V dc/dc and 400 V DCX. Both are designed with a higher operating frequency using printed circuit board windings for the matrix transformer structure, and, furthermore, with synchronous rectifiers directly mounted on the secondary windings to minimize termination loss and leakage inductance.

Such a transformation in the power system architecture offers further opportunity for a significant paradigm shift in the way that power supplies are designed and manufactured in the future. With this modular building block approach,



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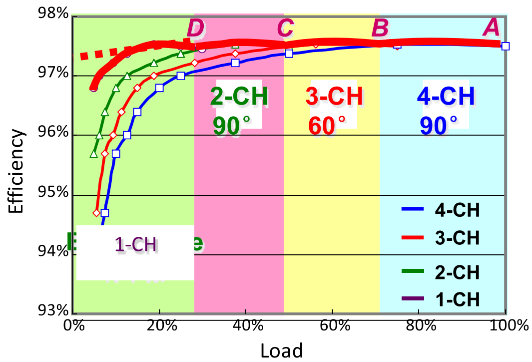
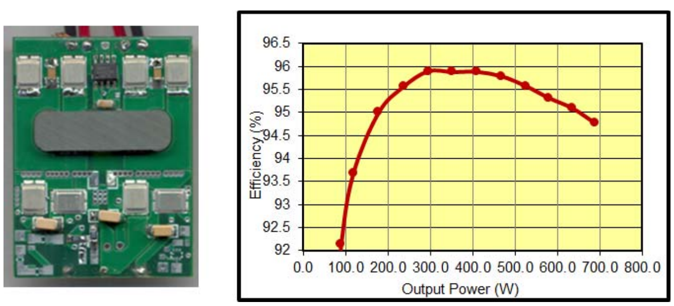
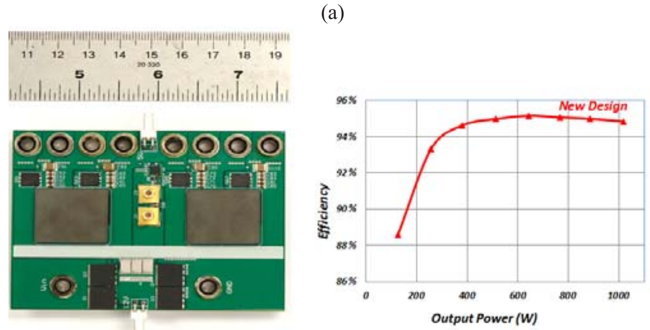


(b)

Fig. 8. (a) Multiphase boost PFC with significant reduction of input filter and output capacitors. (b) Efficiency improvements due to phase shedding and burst mode operation.



(a)



(b)

Fig. 9. LLC resonant converter-based DCX (a) 48 to 12 V operating at 800 kHz with 700 W/in^3 power density and (b) 400 to 12 V operating at 1 MHz with 700 W/in^3 power density.

further integration can be made to improve the efficiency, power density and manufacturability. This is illustrated in the following section.

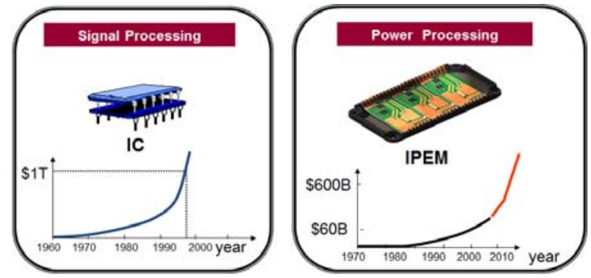


Fig. 10. CPES research vision.

C. Integration Concept

Capturing the trend in DPS, in 1998 the Center for Power Electronics Systems (CPES) was established with the support of the NSF, with the research vision to develop an integrated system approach via integrated power electronics modules (IPEMs) to enable dramatic improvements in the performance, reliability, and cost-effectiveness of electric energy processing systems. The envisioned integrated power electronics solution is based on the advanced packaging of the new generation of devices, and innovative circuits and functions in the form of building blocks with integrated functionality, standardized interfaces, suitability for automated manufacturing and mass production, and application versatility; namely IPEMs, and the integration of these building blocks into application-specific systems solutions [49]. The intended impact of this paradigm shift can be compared with the impact realized via the improvements in very-large-scale integrated (VLSI) circuit technology that has enabled significant advancement in computer and telecommunications equipment; see Fig. 10.

The IPEM approach makes it possible to increase levels of integration of devices, circuits, sensors, and actuators into standardized manufacturable subassemblies and modules that, in turn, are customized for a particular application. A competitive advantage will be gained by industries that can quickly and efficiently provide their customers with a level of customization and flexibility that is now routine in VLSI circuit technology. In addition, as processes become established, industries that make use of standardized components, subassemblies and modules will be able to enjoy the savings associated with economies of scale. All opportunities for new applications, dismissed in the past because of high cost, will for the first time be practical due to the economy of scale and will unearth a large new market.

D. Integrated Power Electronics Modules

The dramatic improvements that are required in the performance, reliability, and cost-effectiveness of electric energy processing systems can only be achieved by developing an integrated system approach based on the advanced packaging of new generations of semiconductor devices, and innovative circuits in the form of building blocks with integrated functionality, standardized interfaces, suitability for mass production, and application versatility.

The fundamental functions needed in a power electronics system include:

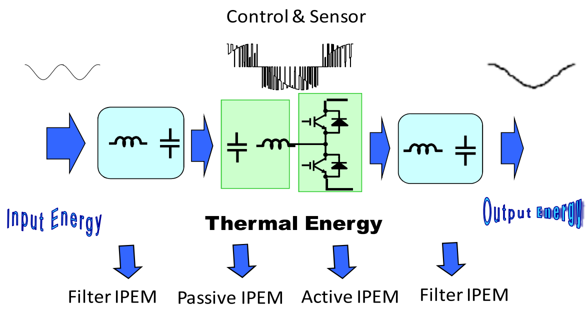


Fig. 11. Function partitioning into cells for electronic energy processing.

1) switching elements;
2) control to execute all operation correctly, both spatially and temporally;
3) electromagnetic energy storage and transformation;
4) EMI filters;
5) thermal management;
6) mechanical/structural stability of components, modules, and total assembly.

The proposed IPEM approach is an effort to integrate most if not all the constituent technologies embodied in power electronics technology described in the previous section.

An analysis of the partitioning in terms of functionality in energy processing systems leads to a possible system partition with the active IPEM, integrating the electromagnetic passive functions as a passive IPEM and an EMI filter IPEM, as shown in Fig. 11.

E. Integrated Power Electronics Systems via IPEM—Example 1

The DPS front-end converter shown in Fig. 12 is used as an example to demonstrate the IPEM approach at the module and system levels [36]. A high-voltage MOSFET and SiC diode set in a boost configuration are chosen for switching at 400 kHz. For good thermal management, two parallel MOSFETs and two parallel SiC diodes are adopted. The maximum operating junction temperature is limited to < 125 °C.

The zero-voltage-switched asymmetrical half-bridge converter (AHBC) provides isolated dc–dc conversion from 400 to 48 V. The secondary converter has a current-doubler topology. The switching frequency is 200 kHz, and the maximum operating junction temperature is limited to less than 125 °C.

Fig. 12 identifies the three converter building blocks as an EMI filter IPEM, an active IPEM, and a passive IPEM. The active IPEM represents the integration of power MOSFETs and gate drivers, for both the PFC and dc/dc stage. The main goals of the overall integration are to reduce the component count, increase power density, develop a modular approach, improve thermal management, and reduce the overall number of interconnections at the system level.

1) EMI–Filter IPEM: The typical structure of an integrated passive structure to be used as an EMI filter is shown in Fig. 13. A dielectric sheet, metalized on both sides to form a winding, is inserted into a planar ferrite core. The four terminals of the two-layer spiral winding are named A, B, C, and D. The capacitance and inductance are distributed along the winding, so the equivalent circuit functions as a transmission line. The lumped circuit acts as an L-type EMI filter.

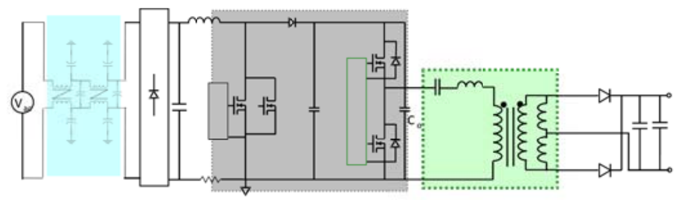


Fig. 12. Integrated front-end converter at 1 kW.

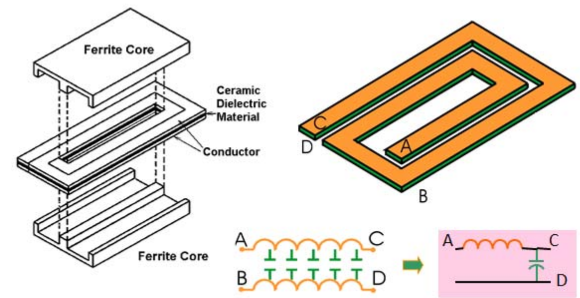


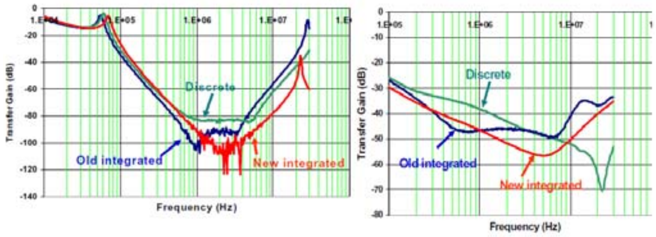
Fig. 13. Spiral winding planar-integrated LC.

Fig. 14. Comparison of discrete and integrated EMI filter prototypes.

Literature [45] and [50] show how the EMI filter can be made of spiral windings in a structure similar to Fig. 13. Two two-layer spiral windings with a dielectric sheet in between them form a CM filter, since each spiral winding has one layer grounded, and the distributed capacitance and inductance form a distributed CM filter. The DM inductance is generated from the leakage flux of the CM inductor by inserting a leakage layer (magnetic material) between the two planar windings. This integrated filter structure enables far better control of the parasitics associated with each of the filter components as well as better control of the interconnected parasitics, which are detrimental to the filter's ability to attenuate the high-frequency noises. For example, it has been demonstrated that the equivalent parallel capacitance of the filter inductors that are detrimental to high-frequency filter performance can be cancelled through proper shielding [51].

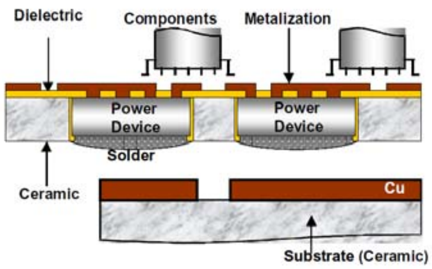
Applying the integration and equivalent parallel capacitor cancellation technologies for integrated EMI filters, an improved integrated EMI filter prototype with structural winding capacitance cancellation was designed and constructed (Fig. 13). To evaluate its performance, a baseline discrete EMI filter with the same component values was also constructed.

The CM and DM small-signal transfer gains for the filter were measured, and are shown in Fig. 15. From these measurement results, it can be concluded that the integrated EMI

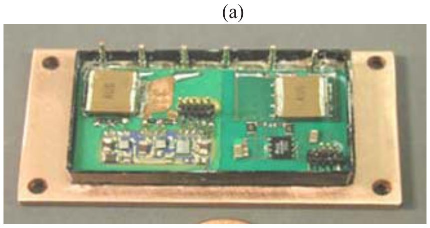


(a) (b)

Fig. 15. Measured EMI filter transfer gain comparison. (a) DM transfer gain. (b) CM transfer gain.



(a)



(b)

Fig. 16. (a) Cross-sectional view of an embedded power active module. (b) IPEM for PFC and dc/dc converter.

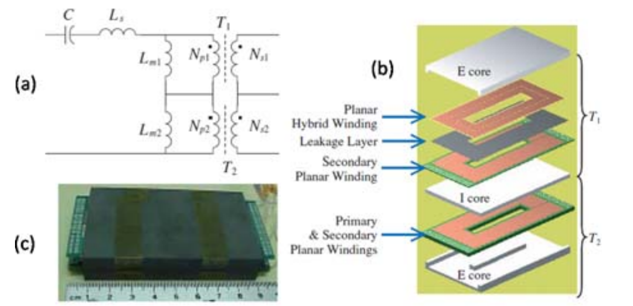
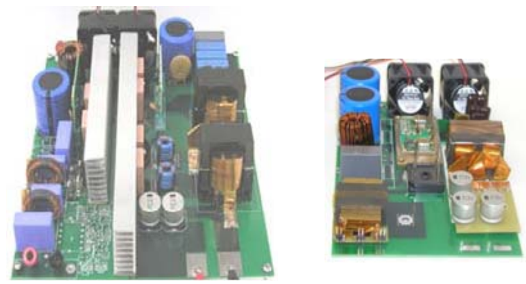


Fig. 17. Components of the passive IPEM. (a) Equivalent circuit. (b) Exploded view of the passive IPEM. (c) 1-kW prototype.



(a) (b)

Fig. 18. Comparison of hardware of front-end converters. (a) Discrete front-end. (b) IPEM-based front-end.

filters have the same function as the discrete versions, but with structural, functional and processing integration. The improved integrated EMI filter has about half the total volume and profile as the discrete filter, but much better high-frequency DM characteristics and similar high-frequency CM characteristics.

2) Active IPEM: Since the use of wire bonding inhibits 3-D structural integration, a number of planar metallization technologies are developed. An example of one of these technologies is the Embedded Power Technology that has been implemented in the active power module of the previously discussed DPS [52]. The principle of this technology is shown in Fig. 16(a), while a module for the DPS is shown in 16(b). Fig. 16(b) shows that the bus capacitors, components for the gate drive, and input pins are mounted onto the top metallization of the PFC and dc-dc stages. The bottom side is wholly soldered onto a heat spreader made of Cu plate. The Cu posts are mounted on the top traces and form the power terminals. Note that as one of the main structural elements of this planar technology is a ceramic carrier, the structure is amenable to mounting passive devices and advanced control functions in a 3-D fashion directly on the carrier.

For high-density integration, the gate drive is assembled on a hybrid circuit with an Al_2O_3 substrate made by thick-film technology. The bare driver chips and components are mounted onto it through wirebond and surface mounting.

3) Passive IPEM: Because of the current doubler configuration, the structure of the passive IPEM was realized by stacking two transformers and using only one dc blocking capacitor, as shown in Fig. 17(a). The transformers are built with two planar E-cores that share a common I-core, as shown in Fig. 17(b). The dc blocking capacitor of the AHBC is implemented in only transformer T1 using the hybrid winding technology [53]. This technology is implemented using Cu traces on both sides of the winding and a dielectric layer placed in the middle to enhance the capacitive component of the winding. The transformer T2 is a conventional planar low-profile transformer. The inductances of the current doubler output filter are realized by the magnetizing inductances of both transformers. Fig. 17(c) shows a picture of the final passive IPEM implemented for the AHBC.

4) Integrated Front-End Converter: To demonstrate the benefits of the IPEM concept at the system level, two 1-kW front-end converters were built using exactly the same topologies; one using discrete devices and the other using IPEMs, as shown in Fig. 17.

The system-level power density of the converter double, and the system's electrical performance has improved as well. The system efficiency is increased more than 2% in the high line voltage range, and more than 3% at 90 V. The major improvement is due to the switching loss reduction by minimizing the circuit parasitics. By replacing the discrete active and passive devices by IPEMs, the whole system only consists of a few modules, which is suitable for automated assembly.

F. 3-D Integration for Point-of-LC—Example 2

Point-of-load (POL) converters are widely used in computers, telecommunication systems, portable electronics, and many other applications. As the power demands increase for POL converters, the bulky inductors and capacitors required to provide this power occupy a large portion of the real estate of

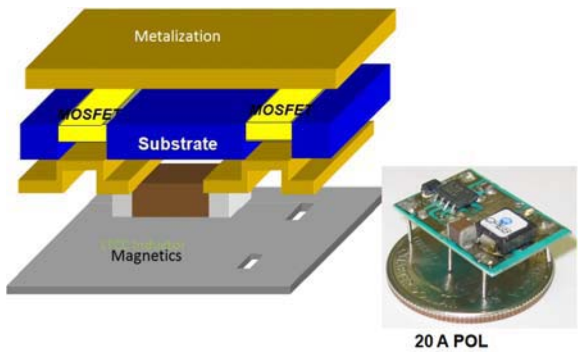


Fig. 19. Integration of higher-power POLs.

the motherboard. To achieve the goals of decreasing the size of POL converters, two things have to happen simultaneously: one is a significant increase in the switching frequency to reduce the size and weight of the inductors and capacitors, and the second is integration of the passive components, especially magnetic components, with active components.

The magnetic integration concept has been demonstrated in the past at levels < 2 A and a power density around 300–700 W/in^3 by using Si-based power semiconductors. Recently, several successful demonstrations of 3-D integration methods have been reported using a magnetic component as a substrate to achieve a very high power density at a high current level [54]–[56].

The basic concept of 3-D integration is to integrate the whole converter vertically. First, very low-profile passive layers are built as a substrate for the whole converter, then the active layers are built above the passive layers. A conceptual diagram of this 3-D integration is shown in Fig. 19. This vertical 3-D integration allows for footprint saving and full space utilization, which greatly increases the converter's power density.

Fig. 20 shows two prototypes of a 5 MHz, 3-D integrated POL converter with IR's GaN devices. Fig. 20(a) shows a single-phase version with 10-A output current, Fig. 20(b) shows a two-phase version with 20-A output current, and Fig. 20(c) shows the efficiency of the single-phase POL converter at different frequencies. At 2 MHz, this integrated POL converter has over 91% peak efficiency; at 5 MHz, its peak efficiency is still as high as 87%. The total converter footprint of the single-phase version is only 85 mm^2. For the single-phase converter, a series of LTCC inductor substrates are designed for operation frequencies from 2 to 5 MHz. These inductors have the same foot-print, but have different core thicknesses to achieve the designed inductance. The power density of the 3-D integrated POL in the converter in Fig. 20(a) is as high as 800 W/in^3 at 5 MHz.

The two-phase POL converter with a coupled inductor has a higher power density of 1100 W/in^3 at 5 MHz, which is a tenfold improvement over industry products at the same current level. The coupled inductor has a core thickness of only 0.4 mm.

Fig. 21 shows a power density comparison between CPES's 3-D integrated POL converters and the industry products.

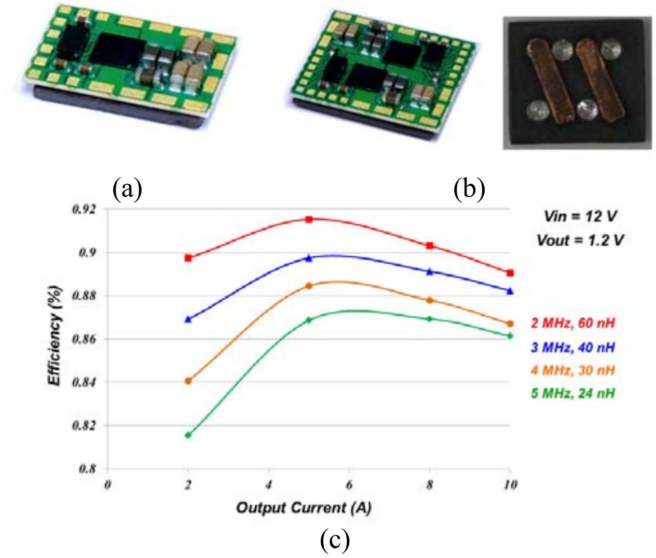


Fig. 20. 3-D integrated POL with IR GaN devices [57]. (a) Single-phase version. (b) Two-phase version. (c) Efficiency of single-phase version.

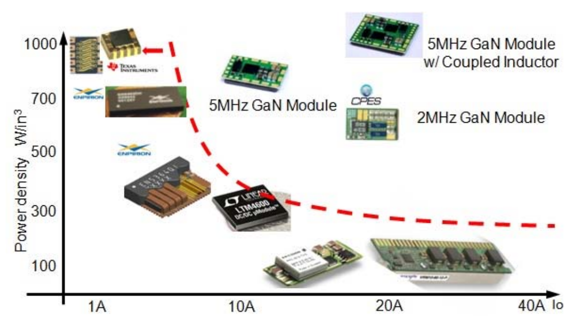


Fig. 21. Power density of POL converters.

It can be seen that the proposed 3-D integration technologies have successfully penetrated the barriers of high density integration for high-current POL converters.

G. IPEM Development and Commercialization

Over the past 15 years, the IPEM integration under support from NSF-ERC has been focused on low powers of up to 10 kW in applications from portable hand-held equipment to motor drives. The development of the IPEM concept for medium- and high-power applications was championed by Office of Naval Research (ONR) and the defense industries as the Power Electronics Building Block (PEBB) approach.

In the motor drives industry, although the concept of intelligent power modules (IPMs) started in parallel with PEBB and IPEM development, the widespread use of IPMs only began in recent years. Major industry leaders, including Toshiba, Mitsubishi, Siemens, ABB, Fuji, IR, Semikron, and Powerex have introduced IPEM products. Today, more than 40% of appliances in Japan are using module-based inverter drives.

In effort toward integration, the power supply industries have been lagging in their development of motor drives, with the exception of certain areas of applications. For example, the multiphase VR module has been adopted as the standard industry solution for powering microprocessors and

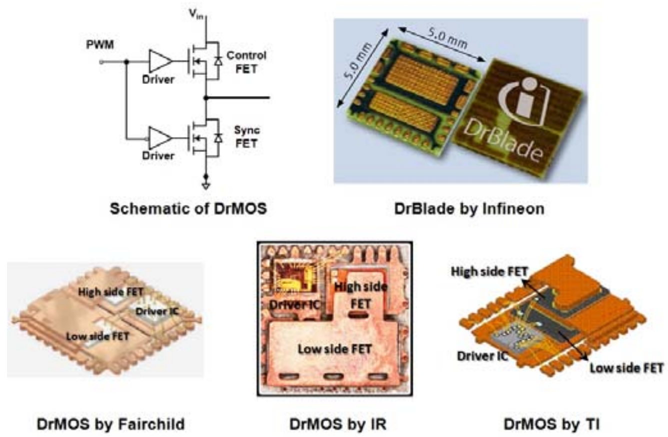


Fig. 22. Integrated modules referred to as DrMOS.

many other applications that require POL power supplies. All major semiconductor companies have participated in the development and commercialization of this technology and have offered new products referred to as DrMOS, which are similar to IPEMs, to improve transient response and integration density, as shown in Fig. 22. Most of the products in this area have already eliminated wirebonds, which has led to significant improvement of thermal management and reduction of interconnect resistance and parasitic inductance. Similar packaging concepts have also been implemented in high-power IPMs. With the recent development of the wide-bandgap devices with materials, such as SiC and GaN, integrating these solutions with advanced packaging is no longer a luxury, but a necessity. It is logical to expect that an approach similar to that described above will occur in earnest in a wide range of power supply applications.

VI. Future Driving Forces

A. Traditional Driving Forces

As stated above, the traditional internal drivers for the development of power electronics are improved switching devices, followed by new and improved topologies. This derives from the original historical philosophy centered on improving the nonlinear element in the system. The previous reasoning in this paper has been that these two fields are very mature, with the exception of the emerging wide-bandgap devices. They have now led to power electronic converters approaching the limits of their possible technical metrics in their present form. This leads one to expect driving forces from some of the other (external) constituent technologies (e.g., packaging, EMI filter, and control) and their applications. It is not to be expected that these will totally substitute for the driving forces from devices and topologies, but that they will certainly be much stronger than in the past. Simple examples from the Power Supply ATS have been used to illustrate this viewpoint.

B. What Will Drive the Future of Power Electronics Technology?

Electric energy technology is reaching the point in our global society where all the important functions in our society can only be maintained by the continued presence and expansion of the availability of electric energy.

Power electronics is the engineering discipline utilized to convert electrical power from one form to another. The enabling infrastructure technology is manifested through the increased energy efficiency of equipment and processes using electrical power, and through higher industrial productivity and higher product quality, which results from the ability to precisely control the electrical power for manufacturing operations.

The 2003 EPRI Electricity Technology Roadmap identified high-efficiency end-uses of electricity as one of the key limiting challenges, with high-efficiency lighting systems and high-efficiency motor drives and power supplies among the highest-priority capability gaps. Further improvements in energy conservation and its associated environmental impact cannot be accomplished without a significant paradigm shift in power electronics technology.

The prohibiting factor preventing the widespread use of power electronics solutions for these energy-saving applications is their relatively high installation cost. The energy savings cannot be realized without a radical change in design and manufacturing practices to provide more affordable power electronics products in mass quantities. The progress of power electronics technology in the last few years; with increasing use of a standard, modular, integrated approach; as well as recent changes in the global economic climate have led to increased penetration of power conversion equipment.

C. Emerging Technologies

Similar to the advanced packaging and integration technologies described in earlier sections for lower-power IPEMs, advanced high-power PEBBs need to be designed with much improved thermal management.

Under ONR programs, numerous PEBB-based power electronics conversion systems have been developed, demonstrating the advanced capabilities attainable by using a modular approach to high-power electronics. High-power PEBB modules have been developed at CPES, with power capabilities ranging from tens to hundreds of kilowatts. Likewise, CPES has been exploring alternative PEBB topologies, soft and hard commutation techniques, control architectures, choices of semiconductor and passive devices, and most importantly the functional and temporal partitioning of PEBB modules. The latter work has proved essential in determining the structure of PEBBs and what components should be functionally integrated into the modules.

The validity of the modular approach embodied by the PEBB concepts has been further proven by one of the leaders of the electric power industry, ABB, into the multimegawatt range. This paper must be further developed for future needs, and embraced by the industry at large to support the penetration of high power electronics into applications. According to the EPRI survey [58], only 40% of the electric power being used was processed through some forms of power electronics devices. For a sustainable society, it is expected that 80% of the electricity should be processed by power electronics equipment and systems in the future. This presents an enormous opportunity for power electronics engineers.

At the most recent workshop of the series on the future of power electronics that was referred to in Section IV-D [35], the discussions again illustrated the enormous potential in the development of power electronics to be driven by such emerging technologies as the changing power grid structure, an intergrid or future electronic energy network, offshore wind power, multilevel cascade converters for interconnection, high-voltage dc transmission solid-state transformers in traction and smart grids, dc grids and new medium-voltage grid technology, large battery storage, megawatts in power grids, and new control technologies [35].

VII. Conclusion

The observation that power electronics technology may be becoming a mature field after a lifetime of at least a century—as many other technologies before it—was an important motivation to critically examine the present state-of-the-art and possible future development. In this process it is important to understand historically how and when the original driving philosophy for the spectacular development of power electronics technology has come about.

On the evaluation of the state-of-the-art, it can indeed be concluded that the historical development of power electronics technology is approaching the limits of the most important internal metrics of the technology in its present form. This is a definite indication of maturity in the internal development process. It is also clear, however, that upcoming maturity only applies to the internal constituent technologies of power semiconductor switch technology and power electronic switching network technology.

Examples from the power supply technology space have illustrated the scope for driving the further development of the constituent technologies of power electronics by emerging applications. The external power electronics constituent technologies of packaging, manufacturing, cooling, control, and sensing and environmental impact technology are not only in their infancy and will provide enormous research, development, and application possibilities—BUT will only be driven from outside by the emerging future applications!

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