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Integration—A Major Driver of Power Electronics Innovation

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Integration—A Major Driver of Power Electronics Innovation

Jonas Huber, Thomas M. Jahns, and Johann W. Kolar

(Special Section on Visionary Papers)

Abstract—Integration is a fundamental innovation vector and features prominently among the X-Concepts of power electronics (modularization, decentralization, digitalization, hybridization, integration) that facilitate x-times performance improvements, utilizing basic scaling laws. After briefly introducing these X-Concepts, the paper takes a holistic perspective on integration in power electronics and highlights the various aspects beyond the typical focus on maximizing power density of components and building blocks by means of advanced packaging and manufacturing methods: Integration concepts exist on all hierarchical levels of power electronics functional elements and units (materials, component, building blocks, converters, systems, and systems of systems), and encompasses not only the hardware but also the software/control domains, especially on the higher hierarchical levels. Salient examples for integration on all levels are provided. Moreover, we discuss benefits and barriers of integration in power electronics, and challenges and opportunities for academic research. There is an immediate need for research to drive integration on all levels in combination with the other X-Concepts. Thereby, new tools for the multi-domain design of highly integrated systems are necessary, which should also inform digital twins of hardware realizations to enable augmented-reality experimental analysis, i.e., enhancing measured terminal waveforms by estimates of non-accessible inner quantities, possibly using artificial intelligence and/or machine learning. Finally, we consider power electronics integration in the wider context, i.e., complementing technological by economical and environmental aspects, which leads to the “Integration Trilemma” representing the three key competing requirements in the context of integration: ultra-compact realizations of units with specific functionality, low costs/economies of scale through standardization, and, importantly, the dismantlability at the end of life, which is crucial for facilitating repair, refurbishment, and recycling, i.e., compatibility with a future circular economy: Power Electronics 5.0, which refers to the general next step of power electronics development where X-Concepts etc. are implemented in an environmentally compatible form.

I. INTRODUCTION

ANSWERING application demands, the (traditional) fundamental innovation vectors in power electronics aim towards higher functionality, smaller volume, lower losses, and better reliability at lower cost, see **Fig. 1**. Integration is inherent to innovation and thus appears among the fundamental principles of the theory of inventive problem solving [1]. Consequently, integration has been and is a major driver of power electronics innovation, complementing other concepts in improving the key performance indicators summarized in **Fig. 1**.

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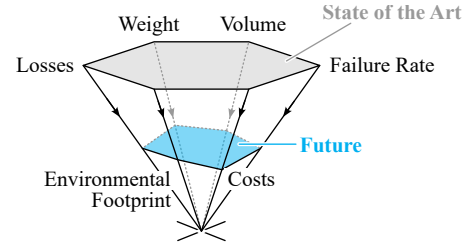


Fig. 1. Key performance indicators of power electronic systems and targeted future improvements. Figure based on [9].

Integration in power electronics was initially driven by the aim of replicating the huge success in the world of integrated circuits (ICs) [2]. In 1959, Robert Noyce of Fairchild Corp. wrote that “it would be desirable to make multiple devices on a single piece of silicon, in order to be able to make interconnections between devices as part of the manufacturing process, and thus reduce size, weight, etc. as well as cost per active element,” leading to the first patent on a system of interconnected devices on a single silicon chip [3], i.e., the *homogeneous integration* of transistors—the first monolithic IC. It took then only a few years for the first commercial applications to appear in 1961, and 10 year later, the release of the Intel 4004 marked the start of the microprocessor revolution [3]. Soon afterwards, in 1965, Gordon Moore observed that the functionality per chip (i.e., the transistor count per chip) doubles roughly every 1.5 to 2 years [4]: Moore’s Law, holding true since more than five decades.¹ Scaling down the feature size of the transistors improves the density and the performance of the digital functions implemented in an IC, but this “More Moore” approach is ultimately limited by physical constraints once the feature size approaches individual atoms [6]. Therefore, further performance enhancements are achieved through functional diversification (“More-than-Moore” approach), i.e., the *heterogeneous integration* of non-digital functions like radio-frequency (RF) communication, photonics, etc., possibly using new materials, into the chip (system on chip, SoC) or into the same package (system in package, SiP) [6], [7], whereby several chiplets are interconnected on an interposer (2.5D), by stacking (3D), or, combining the two, in a 5.5D approach [8].

Similarly, a typical power converter as shown in **Fig. 2a** comprises a wide range of different power and signal compo-

¹Moore’s Law is a special case of an experience curve effect, first described by the engineer Theodore Paul Wright of the Curtiss-Wright Corp. in 1936, who found that for each doubling in aircraft production, the labor time per aircraft reduced by 20% (“Wright’s Law”) [5].

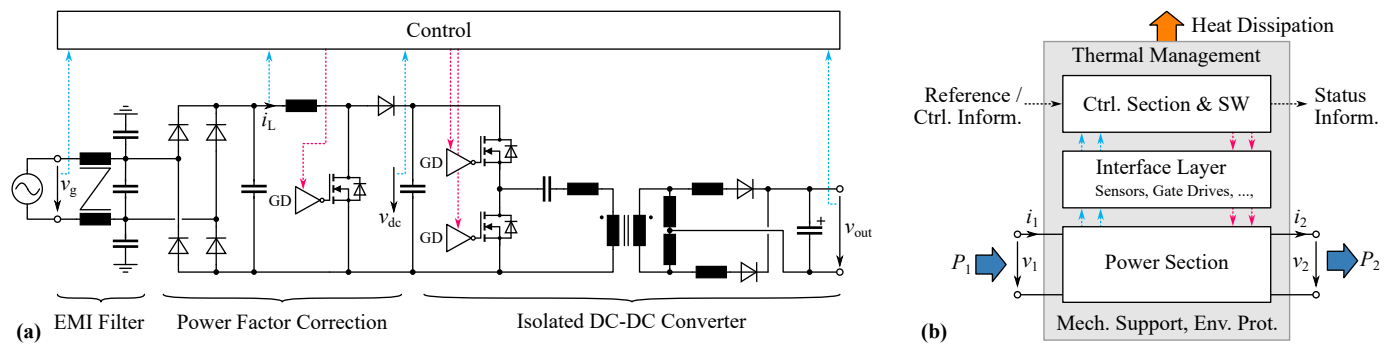


Fig. 2. Functional units of a power converter system. (a) Exemplary circuit topology (single-phase PFC with EMI input filter and downstream asymmetrical half-bridge dc-dc converter [10]). (b) Abstraction into five main functional units (power circuit, signal-power-signal interfaces, control electronics and control software, thermal management, and inner/outer electrical interconnections and mechanical support/enclosure structures).

nent types, structural parts, and software. **Fig. 2b** shows an abstraction into five main functional units, i.e.,

- power circuit consisting of active and passive components (energy storage, galvanic isolation, filtering),
- signal-power-signal interfaces (gate drivers, current/voltage/etc. sensors, etc.),
- control electronics and control software,
- thermal management, and
- inner/outer electrical interconnections and mechanical support/enclosure structures.

Note that alternative, partly similar categorizations have been employed in the literature, e.g., [2], [11].

Integration in power electronics typically involves more than one of these functional units and is therefore mostly heterogeneous. Motivated, as mentioned, by the developments in microelectronics, research in the integration of power converters received significant attention in the late 1990s and early 2000s [2], [10]–[13], likely triggered by a “Power Electronics Building Block (PEBB) Workshop” organized by the Office of Naval Research (ONR) and the Department of Energy (DOE) in the summer of 1995 [14]. Integration approaches in power electronics were classified into the three categories (1) structural integration, i.e., essentially miniaturization, (2) functional integration, i.e., the combination of more than one function into certain parts, and (3) electromagnetic integration, i.e., the use of the same electromagnetic volume for several energy processing functions [12]. Consequently, the focus was mostly on maximizing power density, following the paradigm of active, passive, and filter “Integrated Power Electronics Modules” (IPEMs) introduced by the Center of Power Electronic Systems (CPES) [2], [11]. IPEMs integrate the power processing functions spatially and/or functionally into components with enhanced functionality and/or into building blocks, using specific technologies for manufacturing and/or packaging. The resulting active, passive, and hybrid IPEM building blocks are then further combined to form the power processing part of entire power converters [15]. These concepts have been analyzed in parallel and/or been taken up by industry, resulting in ultra-compact power conversion modules like a recently presented 30 kW, 800 V to 400 V fixed-ratio automotive dc-dc converter with a power density of 550 kW/dm³ (not including the cooling system) and a peak

efficiency above 99% [16].

Targeting higher power levels, the PEBB concept was introduced in the industry in the late 1990s [17], [18]. Similarly, the integration of motor drives into electric motors is another prominent example of integration efforts in power electronics; with research going back to the 2000s [2], the concept has, in the meantime, arrived in the industry, too [19].

This paper introduces a new holistic perspective on integration in power electronics, aiming at generating awareness of the various facets of integration beyond maximizing power density through advanced packaging and manufacturing technologies. Based on discussions at the IEEE FEPPCON XII [20] and a presentation at the PELS Day 2025 [21], we show how integration is not only applicable to hardware but also to the software and control domains. Further, hardware integration is not restricted to components and building blocks, but spans all levels from materials to systems; the paper highlights current developments and variants of integration on these levels. We then explore opportunities and barriers for integration, clearly summarizing the trade-offs and shedding light on aspects currently not in the research focus (like the implications on recyclability of highly integrated power converters), which then leads to the identification of a potential next step in power electronics development.

Throughout the paper, we give many examples and specific references. However, please note that neither the examples given nor the references cited for each example are exhaustive but selected to illustrate concepts discussed in a suitable way and to serve as entry points for in-depth follow-ups by interested readers; the aim is to give a broad overview rather than a fully comprehensive review, which would exceed the scope of a single paper by far.

The paper is organized as follows. First, **Section II** introduces the five X-Concepts in power electronics, one of which is integration. **Section III** then introduces a hierarchical categorization of integration in power electronics from the material to the system-of-systems level, and discusses each level with examples. **Section IV** summarizes benefits and barriers of integration in power electronics, and derives future research vectors, before **Section V** concludes the paper.

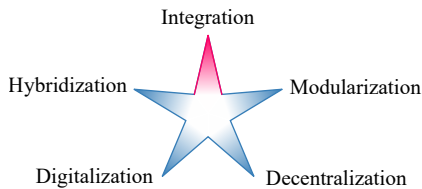


Fig. 3. The five X-Concepts in power electronics [22], which facilitate improvements in performance by factors (“ x -times”) by leveraging scaling laws.

II. X-CONCEPTS

There are five X-Concepts in power electronics [22], i.e., modularization, decentralization, digitization, hybridization, and integration (see also **Fig. 3**). X-Concepts are broadly defined as concepts that open the possibility for leveraging scaling laws to enable x -times improvements in performance; examples will be given shortly. Often, X-Concepts are used in combination to create power conversion systems of highest performance. As integration is among the five X-Concepts, they are briefly discussed in the following.

A. Modularization

The leveraging of scaling laws as the defining characteristic of an X-Concept is probably most clearly visible in the case of modularization, i.e., the splitting of a converter into many identical modules. Typical examples include well-known topologies like the modular multilevel converter (MMC) or the cascaded H-bridge (CHB) converter shown **Fig. 4**. In general, if a given dc voltage V_{dc} must be processed with power semiconductors, splitting this voltage among N essentially series-connected devices with correspondingly lower voltage ratings of $V_{b,N} = V_{dc}/N$ results in significant performance improvements. First, the specific on-state resistance of (unipolar) power MOSFETs scales with the blocking voltage as $R'_{on} \propto V_b^x$ with $x \approx 2.5$ [23], [24], i.e., stronger than quadratically. Therefore, a series connection of several low-voltage (LV) devices shows a lower on-state resistance than a single high-voltage (HV) device, if equal total chip area is considered; i.e., we have $R_{on,N,total} = 1/\sqrt{N} \cdot R_{on}$, where R_{on} denotes the on-state resistance of the HV transistor (rated for V_{dc}) and $R_{on,N,total}$ is the total on-state resistance of the series connection of N LV transistors (each rated for V_{dc}/N) [23]. Furthermore, modularization enables interleaved operation of the modules, resulting in a switched output voltage with an effective switching frequency of $f_{s,eff} = 2Nf_s$ (for a CHB converter) with f_s the switching frequency of an individual transistor, and a multilevel characteristic; thus, for a given device switching frequency and a given filter inductance, the current ripple reduces with $\Delta i_{pp} \propto 1/N^2$ [25]. Alternatively, keeping the current ripple the same as in a non-modular system, a modular CHB converter achieves a reduction of the switching losses with $1/N^3$ [23]. Modularity further facilitates the implementation of redundancy to increase the availability on the system level [25]. Finally, modular systems consist of a high number of equal building blocks, benefitting from economies of scale and experience curve effects. On the other hand,

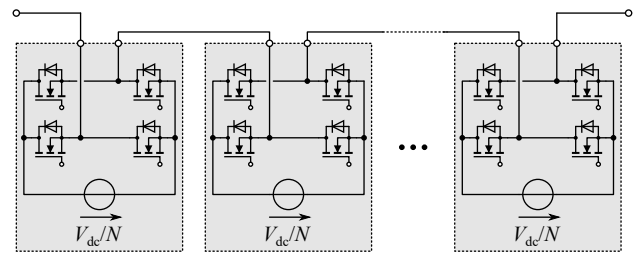


Fig. 4. X-Concept “modularization”. A cascaded H-bridge (CHB) converter performs HV dc-ac power conversion using multiple identical modules realized with LV power semiconductors.

splitting the power conversion functionality into smaller sub-units increases the part count, and, especially for galvanically isolated systems leads to a reduction of the power density due to smaller per-unit power ratings and fixed isolation distances [26], [27]. Modularization thus opens a degree of freedom that must be evaluated considering the overall system and application context.

B. Decentralization

The value of a general network, i.e., a decentralized configuration of nodes with connections in-between, grows more than proportionally with the number of nodes. For communication networks, “Metcalfe’s Law” [28] states that the value of the network V grows with the number of unique connections, i.e., with the number of nodes N squared as $V \propto N^2$, see **Fig. 5**. It is important to stress that decentralization thus also implies the presence of a network interconnecting the decentralized units.

This scaling law indicates how, in general, decentralization can increase the utility of a system. An early basic example is the transition from factories with a central steam engine and mechanical power distribution via a main shaft and belt drives to individual working stations to a full decentralization of the mechanical energy provision by means of electronically controlled electric motors, where often a coordinated control is used to accomplish an overall task. A similar paradigm shift occurred in the transition from centralized mainframes to personal desktop computers and their interconnection via local networks and/or the internet.

In electric power conversion, decentralization can be observed on the signal level, e.g., by the implementation of local control and protection functions such as desaturation detection for the short-circuit protection of power transistors by the local gate drive unit. Large-scale examples include the industrial internet of things (IIOT) at the heart of the Industry 4.0 concept. On the power level, distributed power supply architectures for telecommunication and IT systems [29] facilitate flexible local control and adjustment to power demands, and possibly the inclusion of energy buffering (distributed UPS). Note that such a decentralized system is well suited for scaling-up according to the application’s power demand. Thus, a prime example of decentralization is the transition towards a more distributed generation of electrical energy from distributed renewable resources like solar PV and wind, which relieves grid congestion and might contribute to increased resilience of the power supply [30].

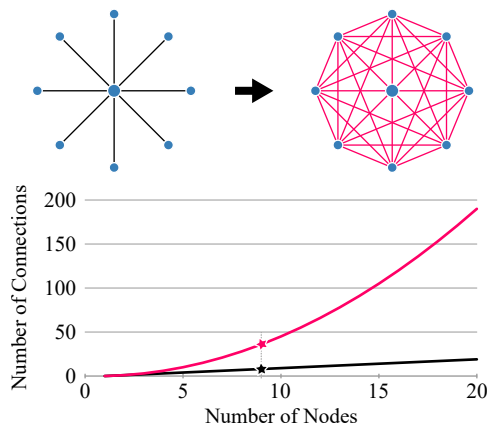


Fig. 5. X-Concept “decentralization”. The value of a network is given by the number of unique connections C , which grows with the number of nodes squared, i.e., $C = N \cdot (N - 1)/2 \propto N^2$ (“Metcalf’s Law” [28]).

C. Digitalization

Digitalization starts with digitization of analog data measurable in the real world. For example, digitization (analog-to-digital conversion) of current and voltage measurements were the first step introducing the transition from analog to digital control of power electronic systems [31], also facilitating data storage. Digital control and communication are fundamental for managing the complexity of modular and/or decentralized systems (note the synergies between the X-Concepts). The massive increase in available computing power (see “Moore’s Law” discussed above), even in low-power embedded controllers, facilitates advanced control methods, predictive maintenance strategies, etc. Further, digitalization creates flexibility through software-defined functionality [32] of non-application-specific power conversion hardware, energy storage modules, etc., as could beneficially be employed in future smart/electronic grid concepts [33].

D. Hybridization

Hybridization refers to a combination of two independent functional units of different types/categories, achieving overall higher performance, as, e.g., in hybrid cars that combine the benefits of an internal combustion engine (ICE) and a battery-electric drivetrain.

In power electronics, hybridization appears in the various forms of partial power processing concepts. For example, splitting the power handling into a HV and an LV share, a cascode configuration of a HV GaN normally-on HEMT and an LV silicon normally-off MOSFET as shown in **Fig. 6a** combines the advantages of both in an easy-to-use switching device. Note that both devices are, in principle, independent and the cascode functionality can be realized from two discrete devices. However, improved performance (e.g., because of minimized parasitics) results from an *integration* (see **Section III**) of the two devices in a die-on-die assembly [34], [35]—another example of the combined application of two X-Concepts.

Partial power processing often implies a splitting of the power handling between a high-power/high-efficiency/low-functionality converter and a low-power/low-efficiency/high-functionality converter—as the high-functionality converter

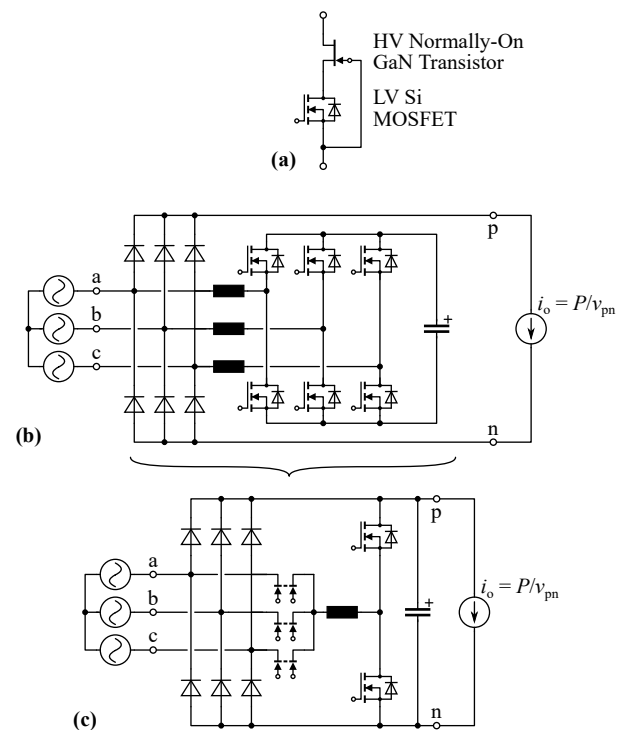


Fig. 6. Partial power processing as an example for the X-Concept hybridization. (a) HV/LV splitting in a cascode switch combining the advantages of a HV normally-on GaN transistor with those of an LV normally-off silicon MOSFET [34], [35]. (b) Splitting of the power processing between a highly robust and efficient grid-commutated diode rectifier and a less efficient forced-commutated active filter, which ensures sinusoidal mains currents by only processing a fraction of the total power. (c) Functional integration of the diode rectifier and the active filter results in the simplified integrated active filter (IAF) rectifier [36].

processes only a small fraction of the overall power flow, its lower efficiency has only limited impact on the overall power conversion efficiency [37]. Correspondingly, **Fig. 6b** shows a hybrid combination of a grid-commutated, robust, highly efficient diode rectifier and a forced-commutated active filter stage, which processes only a fraction of the total power supplied to the load to ensure sinusoidal mains current consumption.² It is important to note that both subsystems can operate fully independently and, e.g., could be realized as two different power converters with independent control and simply connected to the same point of common coupling to achieve the overall same functionality from the grid and load perspectives.

However, again, a further improvement is achieved by combining hybridization with the other X-Concept of integration. **Fig. 6c** shows the thus *integrated* version of the circuit just discussed, i.e., the integrated active filter (IAF) rectifier [36]. Standalone operation of the active filter circuit is not possible anymore, as it relies on the dc voltage provided by the diode rectifier, i.e., the two subsystems are functionally *integrated* and only operable in tandem. Advantageously, the IAF requires only a single inductor and only a single high-frequency-switching bridge leg, highlighting again how combined application of X-

²Note that grid-commutated and forced-commutated are distinctly different modes of operation, and hence the combination of two accordingly operated stages is a hybrid arrangement.

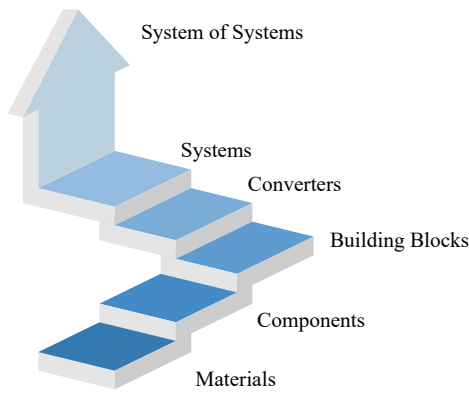


Fig. 7. Hierarchical categorization of power electronics functional units into different levels [21] directly applicable to integration in the hardware domain and mostly also in the software/control domain (see **Fig. 8**).

Concepts (here hybridization and integration) results in further improvements.

Further examples of hybridization in power electronics include hybrid multilevel converters like the hybrid active neutral-point-clamped converter [38], hybrid EMI filters combining active and passive filtering [39], hybrid distribution transformers [40], or, on the control level, the combined phase-shift and duty-cycle control of dual active bridge converters (DABCs) [41].

III. INTEGRATION

Integration is the fifth *X-Concept* and, in a sense, an overarching one that can be advantageously combined with the others in various ways. As discussed in the introduction, typical motivators for integration are lowering the construction volume and/or increasing the functionality in a given volume, reducing the number of functional parts, or lowering the manufacturing effort.

As shown in **Fig. 7**, integration in power electronics can be categorized regarding the hierarchical *level* of the functional unit on which the integration occurs, i.e., material, component, building-block, converter, or system level. As will be discussed below, integration can occur *within* a level (e.g., integrating two magnetic components into a single component with just one core), or several entities of a lower level are integrated to form a new entity on the next higher level (e.g., the IPEM approach integrates active and/or passive components into building blocks). Thus, the hierarchical categorization of functional units further indicates a quasi-fractal correspondence of the hierarchical levels.³

We further argue that integration in power electronics on the building-block level and above is not only used with respect to hardware but also with respect to software and control. For these levels, **Fig. 8** visualizes the three dimensions of power electronics integration, where the *degree* of integration regarding hardware is a continuum between

- basic or spatial integration (shared use of basic functional parts like the base plate of a power module), and

³For example, power converters and energy storage units on the system level correspond to switches and inductances, etc. on the converter level.

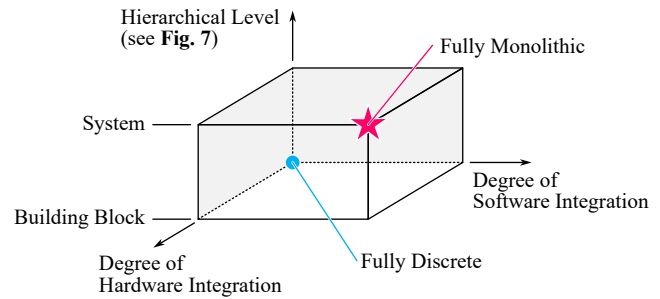


Fig. 8. Integration in power electronics on the building-block level and above (see **Fig. 7**) occurs regarding hardware *and/or* software/control.

- advanced or multi-functional integration, i.e., the combination of several basic functionalities in a new element of higher functionality. Advanced integration is typically also spatial in nature and often monolithic.

The degree of integration regarding software and control similarly varies between complete independence of individual units to fully integrated/coordinated control of an entire network of interconnected devices. The third axis characterizes the hierarchical *level* on which integration occurs according to **Fig. 7**. Thus, many applications of the integration concept in power electronics appear inside of the space highlighted in **Fig. 8**, which can be characterized by two extreme points: (1) A fully discrete realization of a power conversion function, i.e., using discrete components soldered to a common PCB and very specific and minimum control functionality. (2) Full monolithic (i.e., on-chip) integration of a complete power conversion *system* including power and control hardware as well as control software.

This motivates our perspective on integration, which aims at broadening the classical focus on component, building-block, and converter levels, and mostly considering the hardware domain only [2]. In the following, we follow the hierarchical categorization of functional units from **Fig. 7**, illustrating hardware and/or software/control integration on each level with salient *examples*; a comprehensive presentation of the vast body of research would be far beyond the scope of this paper.

A. Material Level

Integration on the material level results in composite materials that combine favorable properties of their constituents and/or feature new properties arising from the interaction of the constituents. Thus, in a general sense, the doping process that forms the basis of all (power) semiconductor technology can be viewed as an integration of a semiconductor material like silicon and dopant atoms like phosphorus (creating an n-type semiconductors) or boron (creating a p-type semiconductor); the same argumentation also applies to silicon carbide (SiC) or gallium nitride (GaN) power semiconductors.

Another example for favorable properties arising from the combination of the constituents is the additive manufacturing of soft magnetic materials from two paramagnetic (i.e., non-magnetic) powders. The process further enables on-line (during the manufacturing process) adjustment of the magnetic properties of the work piece in creation [42]. Thus, three-dimensional

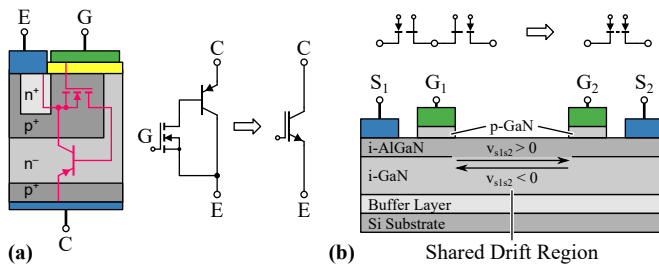


Fig. 9. Component-level integration of active devices. (a) An IGBT is a monolithic integration of a voltage-controlled MOSFET and a BJT. Image based on [46]. (b) The monolithic integration of a common-drain arrangement of two GaN transistors enables bipolar voltage blocking capability utilizing the same drift region and hence lowering the chip area requirement for a given on-state resistance by a factor of four compared to a non-integrated/discrete alternative.

tailoring and grading of the material properties can be realized, which opens new degrees of freedom in the design of magnetic components and electric actuators. For example, introducing a radial permeability gradient in nanocrystalline toroidal cores results in a uniform flux density distribution and hence a lower radial temperature gradient [43].

Finally, composite materials can combine favorable properties of their constituent materials, as, e.g., in the integration of fiber-like aluminum nitride single crystals into resin (resulting in a composite resin with enhanced thermal conductivity) or into ceramics, resulting in a composite ceramic material with improved mechanical strength suitable for, e.g., baseplates of power modules [44]. Similarly, conductive elastomers, e.g., silicones loaded with electrically conductive particles, are used, among other applications, for gaskets that functionally integrate environmental and EMI shielding [45].

B. Component Level

In general components can be seen as an integration of typically more than one material. Continuing the doping example from above, further integrating n-type and p-type zones in a single semiconductor forms a component such as a diode or a transistor. This illustrates the quasi-fractal relationship between the hierarchical levels from Fig. 7.

Within the component level, there are different possibilities for functional integration of the functions performed by several components into a single, integrated component. For the discussion, it is useful to distinguish between active components (such as transistors) and passive components (such as inductors or capacitors).

1) *Active Components:* The integration of several active power devices into a single entity is typically homogeneous (involving devices of the same kind) and often monolithic (on-chip). For example, conceptually, the monolithic integration of a MOSFET and bipolar junction transistor (BJT) forms an insulated-gate bipolar transistor (IGBT), as shown in Fig. 9a.⁴ Advantageously, the IGBT combines the voltage-controlled gate of the MOSFET with the bipolar conduction characteristic of the BJT, such that conductivity modulation improves the

⁴From another perspective, the IGBT device is, of course, also an integration of differently doped semiconductor regions.

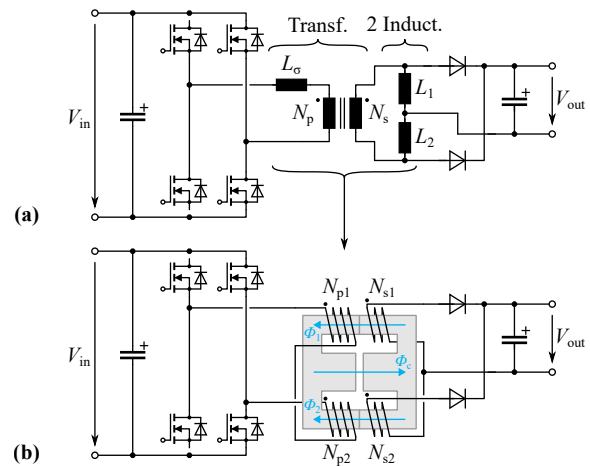


Fig. 10. Component-level integration of passives. (a) Power circuit of an isolated dc-dc converter with current-doubler rectifier, featuring four topological magnetic components (transformer with high leakage inductance, two dedicated inductors), and (b) magnetic integration of the high-leakage transformer and the two inductors into a single component. Figure based on [53], [54].

IGBT's effective specific on-state resistance below that of a unipolar MOSFET device of the same blocking voltage rating, i.e., breaks through the well-known silicon limit.⁵ However, the charge carriers flooding the drift region during conduction must be removed during the turn-off process, resulting in so-called tail currents and high switching losses. An IGBT cannot block high reverse voltage nor conduct reverse current. Both limitations have been removed by further integrating a diode structure with the IGBT, forming either a reverse-blocking (RB-IGBT) [48] or a reverse-conducting (RC-IGBT) device [49].

Similarly, the monolithic integration of two inverse-series (common-drain) connected power transistors results in a dual-gate monolithic bidirectional switch (MBDS), which utilizes the same semiconductor region to block both voltage polarities as visualized in Fig. 9b [50], [51]. Compared to a discrete realization, an MBDS advantageously reduces the chip area required for a given on-state resistance by a factor of four [51], reducing costs accordingly. On the other hand, the smaller chip area renders the thermal management more challenging.

Finally, the cascode arrangement discussed earlier in the context of hybridization, see Fig. 6a, can be realized in a die-on-die arrangement [34]. Such a device can be regarded as a heterogeneous spatial integration of the LV silicon MOSFET and the HV GaN HEMT, realizing a new normally-off HV switch component with straightforward gate drive requirements (like a MOSFET) and the high conduction and switching performance of the GaN HEMT. Going one step further, a monolithic hybrid GaN/SiC FET (HyFET) has recently been demonstrated, which integrates a lateral GaN HEMT structure for defining the switching state and a vertical SiC JFET for voltage blocking, combining the advantages of both technologies [52].

2) *Passive Components:* Fig. 10 shows an example of component-level integration of the multiple discrete magnetic

⁵The silicon limit describes the theoretical minimum specific on-state resistance of a unipolar silicon devices as a function of its blocking voltage [47]; analog (but lower) limits exist for SiC and GaN.

components (transformer, inductors) present in an isolated dc-dc converter with a current-doubler rectifier. The high-leakage transformer and the two inductors of the current doubler are integrated into a single magnetic component using a single magnetic core, which reduces volume, losses, weight, and the part count [53], [54]. Such magnetic integration concepts have been widely employed in power electronics, also including matrix transformer approaches, etc. [55]–[58].

Similarly, electrical functionality and thermal management can be integrated in the same component. For example, magnetic components like medium-frequency transformers [59] or electrical machines [60] equipped with hollow conductors containing a circulating cooling liquid achieve highest power densities.

C. Building-Block Level

Integration of several components and/or functional units into building blocks performing a defined function is essentially at the core of the IPeM concept proposed in the 2000s [2], [11], [15]. In the following, we distinguish between active, passive, and hybrid integrated building blocks.

1) *Active Building Blocks*: A first rather obvious example of an active building block is the ubiquitous multi-chip power module [61], [62], which can be seen as a mostly spatial integration of several power semiconductor chips on shared structural and thermal management components (shared ceramic substrates, baseplate, and housing). Such power modules are more compact, show lower thermal impedance, and higher reliability compared to discrete assemblies. Further, standardized circuit structures (e.g., half-bridge, B6)⁶ and module packages reduce the converter design and assembly effort and facilitate second-source supply strategies. Recent research has reduced the parasitic commutation inductance of such integrated multi-chip half-bridge power modules to values below 1 nH for a 1200 V, 400 A designs though leveraging magnetic cancellation [63].

Taking the integration thought one step further, intelligent power modules (IPMs) integrate not only the power stage but in addition certain control functionality (gate drives, protection) on dedicated substrates in the same package. For motor drive applications, such IPMs are widely commercialized and to some extent standardized, typically including a three-phase inverter power stage, gate drivers, protection, and temperature monitoring. IPMs with power stages realized in both, silicon IGBT and SiC MOSFET technology are available [64], [65], and, targeting lower voltages and power levels, also employing GaN power transistors [66].

Even though *monolithic* (on-chip) integration of HV and LV devices has been considered more difficult compared to LV-only low-power ICs [11], monolithic power ICs in GaN technology have been developed recently. The employed GaN-on-Si technology allows the implementation of LV transistors needed for control functionality and of HV devices for the

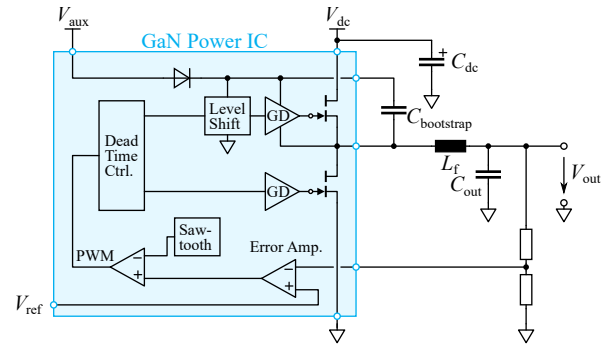


Fig. 11. Building-block-level integration (active components): Monolithic GaN power IC including the power stage, gate drivers, sensing, protection, and control functionality required for buck-type dc-dc conversion. Note that the power passives as well as the thermal management system are still external and not integrated. Figure based on [67].

power switching stage. Such a GaN power IC includes the power stage with integrated gate drivers, sensing, protection, and control functionality, as shown in **Fig. 11**, or certain subsets of these functions, e.g., just the power stage and the gate drivers, etc. [67], [68]. Advantageously, monolithic power ICs feature minimized parasitics, precise matching of components, high reliability, and low footprint and assembly effort on the next-higher (converter) level. However, there are still limitations regarding the monolithic integration of power passives: capacitors would require large chip areas, and on-chip spiral inductors are only suitable for very high frequency applications beyond 30 MHz [67].

2) *Passive Building Blocks*: **Fig. 12** shows an example of a passive building block (or passive IPeM), integrating the functionality of a passive network of inductors, transformers, and capacitors. Specifically, two planar conductors form two windings with dielectric material / distributed capacitance in-between; depending on the external connections of the four terminals, different functionalities of the passive building block are achieved [10]. The arrangement of the two spiral windings can be complemented by magnetic cores and/or by layers of materials with specific permeability or permittivity, i.e., in that sense, there are no parasitics but the overall electromagnetic behavior of the integrated building block is designed to provide the desired functionality described by the targeted equivalent circuit. Advantageously, planar assemblies are compact and well suited for automated manufacturing (e.g., PCB windings), facilitating standardization and cost reductions. Thus, the approach facilitates the realization of passive and/or (EMI) filter building blocks that can be used to complement the active building blocks discussed previously to implement entire power converters.

In a wider sense, also the behavior of piezoelectric resonators [69]–[71] can be seen as an integration of the mechanical and electric domains in a single unit, which again shows an electric terminal behavior similar to a relatively complicated LC-network, possibly including a transformer—i.e., a passive building block.

Last, hybrid excitation systems of electrical machines integrate permanent magnets and excitation windings for the generation of a (partly) variable magnetic rotor flux [72].

⁶Whereas half-bridge configurations are used in ubiquitous voltage-source converters, note that other converter topologies, such as current-source converters, feature commutation cells consisting of three (not two) power transistors and would hence benefit from corresponding power modules integrating an entire three-switch commutation cell.

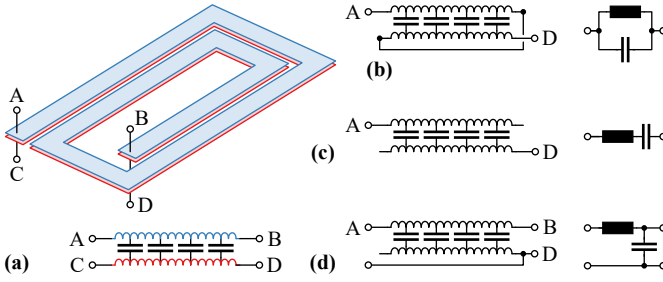


Fig. 12. Building-block-level integration (passive components): (a) Electromagnetic integration of two conductors with distributed capacitance in-between, (i.e., a transformer with integrated capacitive coupling / resonant capacitance). Depending on the external connections, different functionalities described by LC equivalent circuits can be realized, e.g., (b) parallel-resonant, (c) series-resonant, or (d) low-pass filter circuit. The terminal behavior can be tuned by complementing the structure with magnetic cores and/or layers of material with specific permeability and/or permittivity. Figure adapted from [10].

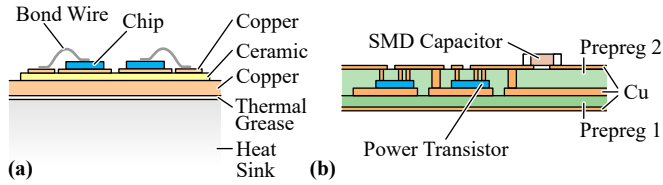


Fig. 13. Building-block-level integration. Conceptual cross sections of a (a) power module as an example for an active building block [61], [62], and of a (b) hybrid building block using PCB-embedding technology to realize a tight integration of different component categories using a common PCB; figure adapted from [73]. Although not shown here, in principle, any surface-mount component could be embedded in the PCB [74]–[76].

3) *Hybrid Building Blocks*: Neither active nor passive building blocks can perform all functions needed for power conversion alone. Therefore, it seems natural to consider also hybrid building blocks, i.e., heterogeneous integration of different active and passive components and/or building blocks using a common packaging technique. For example, PCB-embedding (see Fig. 13) is such a packaging technology that facilitates three-dimensional spatial integration of active components (e.g., power transistor dies) and passive components (SMD capacitors, etc.) using a common PCB substrate, offering high flexibility of the interconnection design, low parasitics and hence high switching performance and low EMI emissions, and high compactness [73]–[77]. In addition to inserting surface mount devices into laser-machined cavities in the PCB, certain passive components can also be *formed* during the PCB assembly process [78]. Further, embedding of optical fibers in the PCB enables high-speed/bandwidth communication [79]; recently, chiplets and chips with integrated multichannel optical transceivers have been introduced [80]. Such optical communication links satisfy very high galvanic isolation requirements and provide excellent noise immunity. Similarly, wireless transmission of signals over short distances, e.g., drive-by-microwave gate control of GaN transistors inside of a building block [81], increases design flexibility by removing the reliance on conductive paths between sender and receiver and combining (isolated) signal and gate drive power supply.

Commercially available integrated building blocks, often using proprietary assembly technology, are available for a wide range of power conversion tasks and voltage/power levels,

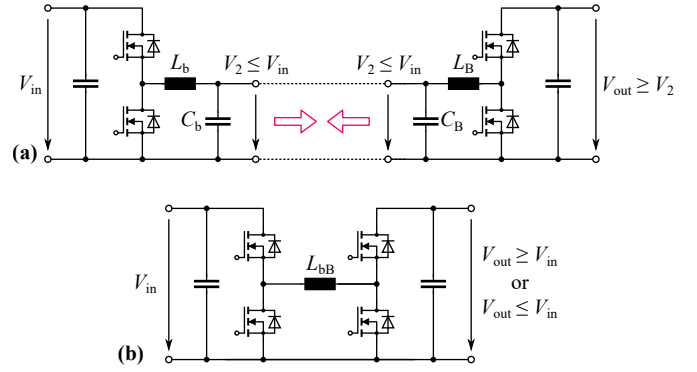


Fig. 14. Converter-level integration. (a) Buck and boost dc-dc converters in back-to-back connection and (b) integrated (non-inverting) buck-boost converter with the two inductors L_b and L_B merged into a single inductor L_{bB} and the two capacitors C_b and C_B omitted.

recently culminating in a 30 kW, 800 V-to-400 V fixed-ratio automotive dc-dc converter with a power density of 550 kW/dm³ and peak efficiency above 99% [16]. Even though such units perform all power conversion functions, including control, they are still only building blocks that must be complemented with thermal management system, buffer capacitors, and structural elements to form a full power converter (see also Fig. 2b).

Targeting applications with much higher voltage and power levels, the so-called power electronic building block (PEBB) concept [14], [15], [17], [18], [82] often employs conventional assembly technology to realize building blocks with a certain functionality. The PEBB concept is widely used in industrial modular high-power/medium-voltage converters, e.g., MMCs, where the PEBBs may include power stage, dc bus capacitors, gate drive, local sensing, protection and control system, low-latency communication interface, thermal management, and isolation coordination with electric field-grading elements in the PEBB housing [83], and possibly also output inductors [84]. Again, full power converters comprise several PEBBs plus further components (like passives) and a converter-level control system.

D. Converter Level

In general, considering the quasi-fractal relation between different hierarchical levels, any power converter can be viewed as an (at least spatial) integration of components and/or building blocks, and a control system, today typically including control software. Integration within the converter level mainly addresses topological/functional integration of two or more converter stages to form a new integrated converter featuring reduced realization effort and/or higher functionality.

1) *Converter-Converter Integration*: Fig. 14 illustrates the current-dc-link type integration of a buck-type and a boost-type dc-dc converter stage, forming a symmetric four-switch (non-inverting) buck-boost dc-dc converter. The buck and the boost inductors are merged into a shared inductor and the two capacitors C_b and C_B can be omitted. Thus, the resulting circuit structure comprises fewer components and requires lower realization effort. Moreover, with a suitable control implementation, the integrated buck-boost converter

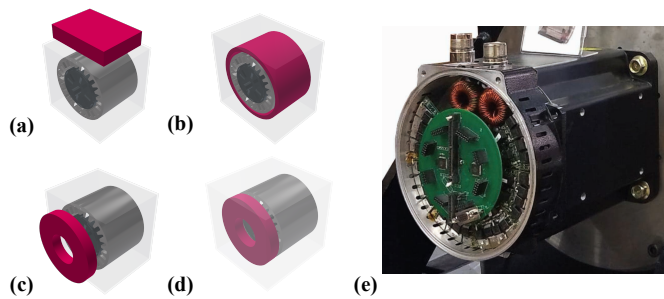


Fig. 15. Hybrid converter-level integration of a motor and an inverter (integrated motor drive, IMD) with different inverter placement options, i.e., degrees of integration: (a) radial housing mount, (b) radial stator mount, (c) axial endplate mount, and (d) axial stator mount; figures based on [95]. (e) Photo of a 3 kW IMD using a current-source inverter topology and the axial endplate mount configuration from (c); image from [19].

allows quasi-single-stage power conversion [85] by operating only either the buck bridge leg *or* the boost bridge leg with high-frequency PWM; alternative operating schemes ensure, for example, optimal ZVS/ZCS conditions using a triangular-current mode (TCM) modulation [86]. This highlights the increasing importance of the control/software dimension of integration on the higher hierarchical levels (building-block level and above).

Similar examples include the integration of a three-phase PFC rectifier with an isolated DAB-type dc-dc converter, resulting in a single-stage matrix-type isolated three-phase ac-dc converter [87], which can achieve very high efficiencies using optimized modulation schemes minimizing transformer currents and ensuring ZVS or ZCS [88]. Thus, single-stage isolated ac-dc power conversion, which is currently of high interest for applications in EV on-board chargers [89], [90], is a salient example for integration on the converter level, including both the hardware and the software dimension.

Further, converter-level integration is sometimes also characterized by a high degree of functional *and* spatial integration. The prime example is the monolithic on-CPU integration of per-core voltage regulators for high-performance microprocessors. Such power supplies on-chip (PwrSoC), sometimes also referred to as power management integrated circuits [91], include the control circuitry, the active power switches, and the power passives, such as microfabricated on-chip air-core inductors [92] and/or deep-trench SOI CMOS capacitors, for example enabling a 10 W, 1.8 V-to-0.7 V...1.1 V on-chip per-core voltage regulator with 85% efficiency, sub-nanosecond response time, and an area power density of 3.2 W/mm² [93].⁷

2) *Hybrid Converter Integration:* The term “converter” should be understood broadly and includes hybrid energy conversion between electrical and mechanical energy or between chemical and electrical energy. In a typical electromechanical energy conversion system, the power converter (variable speed

⁷Note that we consider a PwrSoC as integration on the converter level, because the thermal management and assembly structures are provided from the host CPU. In contrast, concepts integrating CMOS logic and a WBG power stage on a common Si substrate, and include also control and passives in the same package, i.e., power-supply in package (PSiP) concepts [94], do usually not include thermal management and sometimes require a few external components. Therefore, such PSiPs should be rather considered a building-blocks and not as full converters.

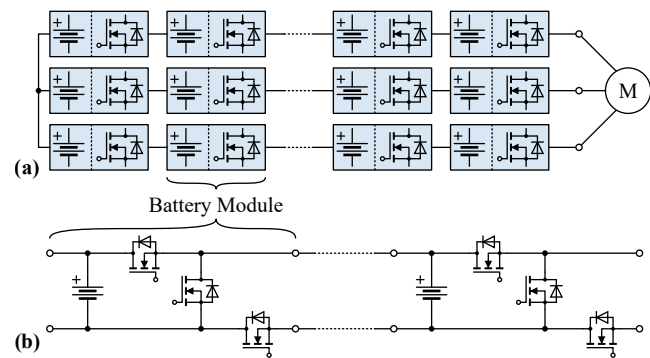


Fig. 16. Hybrid converter-level integration of a battery and an inverter, forming a (a) battery-integrated multilevel inverter (or “ac battery”), where each battery cell is equipped with a (b) LV switching matrix such as the three-switch submodule topology from [103] shown here, allowing to connect battery cells in series, in parallel, or to bypass them.

drive) and the motor are spatially separated and connected (power, encoder signals) with motor cables. The integration of the motor drive and the motor, i.e., integrated motor drives (IMDs) [2], [19], [96], [97], is of high interest due to advantages like increased power density, avoidance of issues caused by long motor cables (overvoltages due to reflected-wave phenomena, EMI cost savings (no expensive shielded motor cables, shared cooling system), simpler connection and setup (possibly usable as drop-in replacement for motors operating directly from the mains without VSD, enabling significant energy savings), relatively straightforward implementation of motor concepts with more than three phases to facilitate fault tolerance (phase loss), and improved manufacturability (e.g., through modularization of the motor and the inverter). On the other hand, new challenges like the power electronics being exposed to high thermal and mechanical stresses (vibration), different lifetimes of the subsystems, and more difficult maintenance arise. Tailoring the trade-offs between these advantages and challenges results in different degrees of integration of the motor drive and the motor being most suitable for a given application, as shown in **Fig. 15a-d** [95]. Further, application-specific IMDs [98] are widespread and often extend even beyond integrating the drive and the motor, e.g., including a mechanical load such as a high-speed turbocompressor [99] or including added functionality such as a gear and accurate position sensing and control for fully integrated robot joints [100]. Finally, note that the integration of drive and motor can also be functional and not necessarily spatial, e.g., by leveraging the motor inertia to buffer the twice-mains-frequency power pulsation in single-phase-supplied motor drive systems [101].

Another example are hybrid electrohydraulic systems that combine the flexibility and controllability of variable speed drives and electric motors with the very high force densities of hydraulic actuators [102].

Similarly, conventional electro-chemical energy conversion systems, for example in an EV, comprise a battery (consisting of many individual series/parallel connected cells and a battery management system) and an inverter; the inverter and the battery are connected via a HV dc bus. Recently, the integration of the inverter into the battery [104] has

gained significant attention: each battery cell (or group of battery cells) is equipped with a switching stage consisting of three or more LV transistors, forming a battery-integrated multilevel inverter [103]–[107]. **Fig. 16** shows an example; many alternative but conceptually/functionally equivalent variants exist. Essentially, the integrated power electronics enable dynamic series/parallel/bypass reconfiguration of the individual battery cells to synthesize staircase phase voltage waveforms; a dedicated active filter series module could operate with PWM to further improve the output voltage quality. The resulting “ac battery” shows very high functionality, i.e., integrates the functions of the battery (energy storage, health management), the inverter (dc-ac conversion for driving the traction motor), and possibly the on-board charger (non-isolated). Further, the systems is highly modular, which comes with advantages such as the potential for leveraging economies of scale as discussed in the context of the X-Concept modularization. On the other hand, the price to pay is a very high complexity of the control system, challenging simultaneous commissioning of both subsystems, high overhead for the galvanically isolated communication links to each module, high equalizing currents if battery cells with unequal state-of-charge are connected in parallel, and comparably higher conduction losses [108]. Finally, note again how here integration involves not only the hardware dimension but also the control/software dimension: the overall control of the “ac battery” must synthesize the correct output voltages to control the motor currents while at the same time ensuring SoC balance among the battery cells, avoiding the parallel connection of battery cells with different SoCs, etc.

E. System Level

Integration on the system level involves two or more individual converters (and potentially further functional units), which are not necessarily physically close or spatially integrated, but controlled/operated in a coordinated way, i.e., the software/control dimension becomes the dominant mode of integration.

1) *Converter Clusters*: In many applications, a system of two essentially independent but series-connected converters is used to realize a desired target functionality. A prominent example are two-stage arrangements of a three-phase PFC rectifier stage and a downstream isolated dc-dc converter as shown in **Fig. 17**, for example used as battery mains interfaces for EV charging applications. In principle, the two converter stages can operate fully independently, i.e., the PFC rectifier can be used to shape the mains currents and regulate the common dc bus voltage while the isolated dc-dc converter controls the output voltage. However, coordinating the control of the two stages, i.e., implementing integrated synergetic control, improves the overall performance of the system significantly. Specifically, considering the circuit from **Fig. 17** based on a Vienna Rectifier (VR), the isolated dc-dc converters shape the common dc-bus voltage v_{dc} to follow the maximum absolute values of the mains line-to-line voltages, resulting in the characteristic six-pulse voltage waveform shown in the figure. Then, the voltage applied by the dc-dc converters controls the current flowing

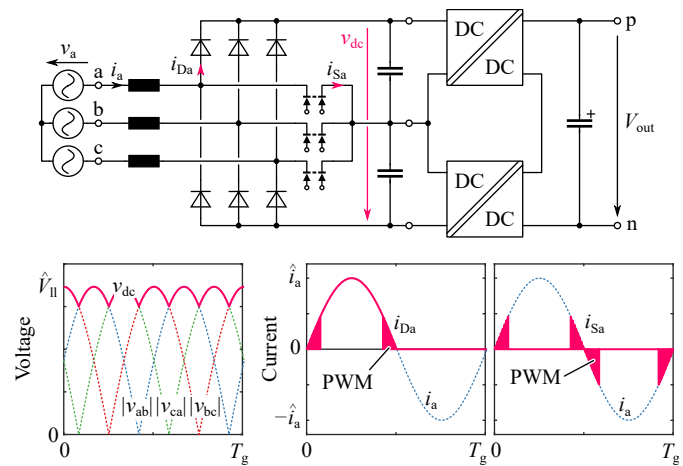


Fig. 17. System-level integration: The performance of a two-stage—Vienna Rectifier (VR) PFC and isolated dc-dc converter, here split into two equal modules—power converter can be significantly increased by integrated synergetic control of the two stages. The dc-dc converters shape the common dc-bus voltage to enable 1/3-PWM operation of the VR, reducing switching losses to less than 1/3 [109].

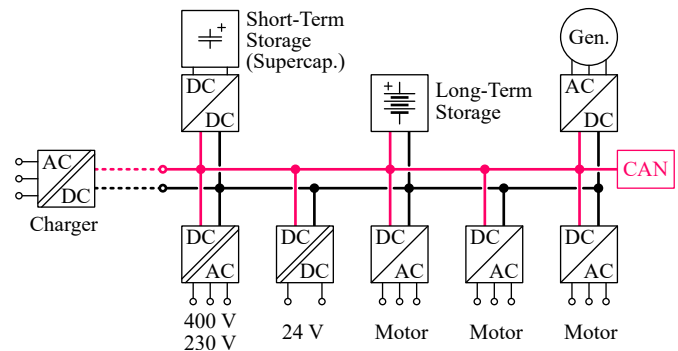


Fig. 18. System-level integration of an EV on-board nanogrid as an example of a hybrid system. Integrated control of all units enables energy management and system-level performance optimization; a communication network is of equal importance as the power network. Figure adapted from [110].

in the two conducting diodes of the VR, and only the current of the third phase (carrying a relatively low current) must be controlled by PWM operation of only one of the three VR bridge legs (“1/3-PWM”)—compared to independent control, thus, the switching losses of the VR reduce to less than 1/3 [109].⁸

2) *Hybrid Systems*: Hybrid systems include not only power converters but involve further subsystems such as energy storage systems, e.g., forming a smart grid [111], a smart city (including in addition, e.g., transportation systems), or, as shown in **Fig. 18**, an EV onboard dc micro/nanogrid [110]. Here, the operation of the individual subsystems (converters like the traction inverters, the on-board charger, auxiliaries, etc., batteries, and even an internal combustion engine) is integrated via an overall control / energy management system. The coordinated exchange of energy thus relies on a system for the continuous exchange of

⁸The switching losses reduce to less than 1/3 because in addition to just one bridge leg instead of three switching at the same time, high-frequency PWM operation is only necessary near the zero crossing of the mains current. hence, the average switched current is lower than for conventional operation, where each bridge leg operates with PWM during the entire mains period.

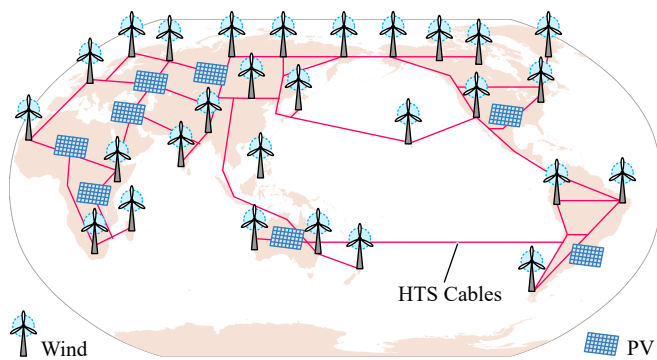


Fig. 19. System of systems: The “global grid” enables trans-continental renewable energy supply using high-temperature superconducting (HTS) cables and signal/software interfaces to facilitate worldwide energy trading. Figure redrawn from [113].

data and signals, i.e., a communication network between the individual converters is as important as the power connections. Whereas certain low-level control and protection functions are typically still distributed/decentralized (see X-Concept decentralization), integrated control of all subsystems enables continuous diagnosis and optimization of overall system-level performance indicators such as overall energy consumption.

Finally, targeting net-zero carbon emissions, our future energy supply should be based almost exclusively on renewable sources, which inherently have an electric interface. However, the future energy system will not be all-electric, as also a future society will require non-electric energy carriers such as heat/cold and hydrogen-based synthetic fuels (ammonia, methanol) for long-haul transportation and long-term energy storage. Thus, a future net-zero emissions multi-carrier energy system [112] integrates these subsystems as well as the necessary cross-sector energy converters, requiring coordinated operation of the heterogeneous subsystems (i.e., the integration again is mostly in the software/control domain).

F. System of Systems

Finally, again following the quasi-fractal relation between hierarchical levels from **Fig. 7**, several such heterogeneous systems of converters and other entities (renewable energy sources, energy storage, cross-sector conversion systems, etc.) can be integrated into a larger network, i.e., into a system of systems.

Fig. 19 shows the global grid concept as an example. The global grid, which has been proposed in various forms over the decades, e.g., in [113], [114], is a worldwide interconnection of power systems with locally connected renewable energy resources. Such a system of systems, ideally, would allow for continuous trans-continental supply and trading of renewable energy around the world, potentially minimizing local energy storage needs, i.e., to operate the overall system of systems in a technically and economically optimal way, increasing the utility or the value of the network (see also “Metcalfe’s Law” in **Fig. 5**). Thus, the integration into the system of systems requires power connections and especially also signal/software interfaces (e.g., for control and energy trading)—the actual

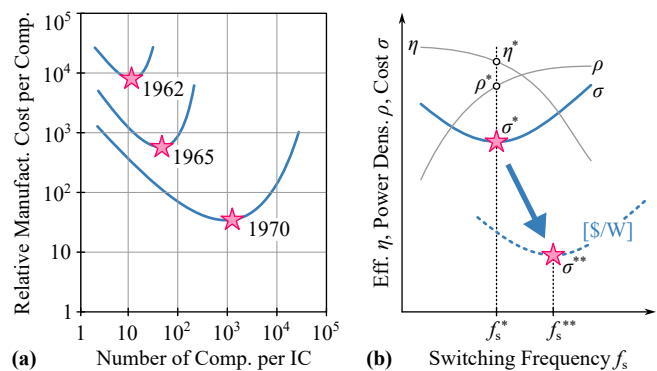


Fig. 20. (a) Gordon Moore identified an optimum (in the sense of minimizing cost per component) of components per integrated circuit in his seminal 1965 paper. The minimum rapidly shifts to higher numbers over time, which results in the regular doubling of the number of transistors per chip commonly known as “Moore’s Law”. Figure redrawn from [4]. (b) Similarly, for a given power electronic converter type, a technology node characterized by switching frequency f_s^* , efficiency η^* , power density ρ^* , and minimum cost σ^* shifts towards lower minimum cost σ^{**} as technology advances over time and higher switching frequencies f_s^{**} become feasible [9], [115].

integration happens almost exclusively in the software/control dimension.

IV. A VISION OF THE FUTURE OF INTEGRATION

Interestingly, at the heart of what is today known as “Moore’s Law” (i.e., the regular doubling of the transistor count per IC mentioned in the introduction) was the observation that there is an optimum number of components per IC that minimizes the cost per component, as shown in **Fig. 20a**: increasing the component count beyond the optimum value, decreasing yields lead to increasing costs per component. This minimum shifts to higher numbers of components over time, i.e., to higher degrees of integration [4]. Similarly, even though signal processing is inherently different from energy conversion, where, e.g., already minimum conductor cross section requirements for a given current ultimately limit the achievable power density, a similar observation holds for power electronics: For a given converter type, there is a switching frequency resulting in minimum cost, and the cost minimum shifts to higher switching frequencies with technological progress as indicated in **Fig. 20b** [9], [115]. In the same way, even though integration in power electronics is more heterogeneous than in the case of ICs, it must be expected that there is an (application-specific) optimum degree of integration.

The previous section discussed integration in power electronics on all hierarchical levels from materials to systems of systems, and considering both, the hardware and the software dimensions. This forms a solid basis for the following analysis of benefits and barriers to integration in power electronics, considering the broad view introduced above. We specifically also address challenges and opportunities for corresponding research in academia, and end with an outlook on future research vectors.

A. Benefits and Barriers

In general, the evaluation of benefits and barriers of integration concepts should consider economic, technologi-

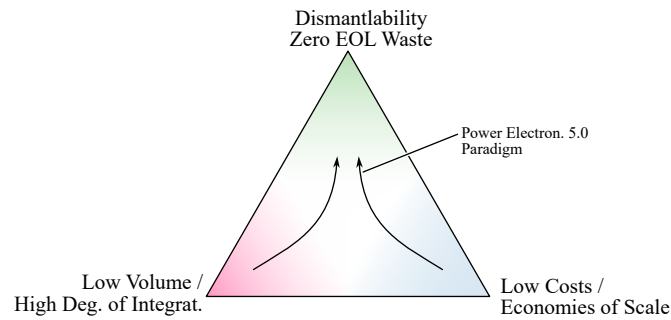


Fig. 21. “Integration Trilemma” indicating the main trade-offs inherent to integration in power electronics [20].

cal/technical, and environmental aspects. Depending on the application and on the hierarchical level, different criteria might be weighted differently. The following discussion centers around the building-block and converter level, but generally applies to integration on all levels.

In quite generic terms, integration leads to the elimination of components and interfaces, reducing functional volume (improving power density or function density) and hence reduces raw material usage. Such highly integrated power conversion building blocks, recently referred to as *Power Chiplets* [116], usually require fully automated manufacturing processes and facilitate automated manufacturing on the next higher level, thus lowering costs and improving quality and reliability. Often, integration results in a minimization of circuit parasitics, for example, enabling faster switching and thus improving power conversion efficiency. Integrating sensing, control, and local intelligence with the power stages enables higher utilization of the components, fast protection, and ultimately IIOT concepts. Finally, integration hides complexity from the next-higher level, i.e., essentially from the designer and, last in the chain, from the user, possibly enabling plug-and-play power converters. Integration thus contributes to simplifying the application of power converters on the system level, where the focus then shifts mostly towards the interconnection with data networks. This simplification is necessary to bridge the gap between a massive expansion of electronic power conversion needs in the context of the reshaping of the energy system towards more and more renewable supply on the one side, and the lack of qualified personnel (in the sense of having expertise in the inner workings of power converter systems) due to an aging workforce on the other side [117].

On the other hand, the close proximity of power and signal component can cause higher thermal and mechanical stresses and increase EMI levels inside of the integrated unit even while EMI emissions to the outside improve. Realizing the same function with fewer, integrated devices (e.g., one MBDS instead of four standard transistors) leads to higher (thermal) component stresses and/or to higher control complexity (e.g., four-step commutation of matrix converters [118]). Further, the often highly specific functionality of integrated units limits opportunities for leveraging economies of scale and might be incompatible with the widely-employed second-source supply chain paradigm. A higher internal complexity of a single integrated unit, i.e., higher entropy, comes with a more complex

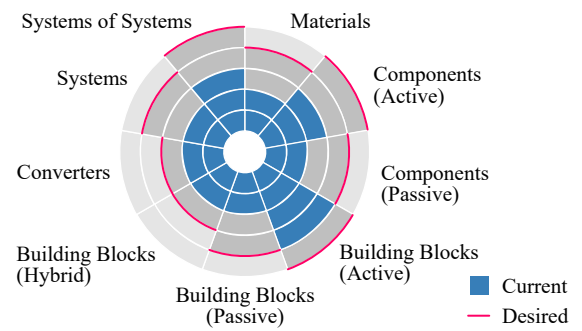


Fig. 22. Exemplary (arbitrary) visualization of application-specific desirable degrees of integration (defined considering aspects depicted in **Fig. 21**) on the different hierarchical levels for informing R&D strategies, e.g., regarding a next product generation. A gap between the desired and the current degree implies need for research and development.

design process and challenges in testing (accessibility of signals of interest). Complex material mixes and high compactness limit reparability and, at the end-of-life, the recovery of critical raw materials.

A real-world example of how these barriers interact may be instructive. While the proven life-cycle and environmental rewards (e.g., greenhouse gas reduction) for integrating the power converter into the same enclosure as its load/source can be very high in some major integration candidates such as electric machines, the combination of barriers/challenges are formidable. Using integrated machine drives (IMDs) as an example, the thermal and vibration environments inside machines significantly increases the stress levels that the drive electronics must endure throughout the product’s lifetime. The fact that the reliability expectations for the integrated drive electronics are very high, exceeding 25 years in many industrial applications, makes the impact of the elevated thermal/vibration stresses even more challenging to overcome. Furthermore, the integrated drive electronics must fit within the envelope dimensions of the original machine in many cases for retrofit applications. Finally, the barriers to wider adoption of IMDs include the low price premium that is acceptable in the marketplace for the integration of drive electronics, regardless of its overwhelming life-cycle energy cost savings.

The “Integration Trilemma” shown in **Fig. 21** summarizes the main trade-offs inherent to many forms of integration in power electronics [20]. For example, extreme power density implies difficult dismantlability and material separation at the end of life, but these are needed for future circular economy compatible power electronics [119], where, for example, a design for disassembly [120] paradigm should be followed. Similarly, the specific functionality of extremely integrated units is at odds with benefiting from economies of scale.

The above discussion and, in particular, the main trade-offs summarized in **Fig. 21** indicate that the usefulness of integration on certain levels and/or regarding hardware and/or software/control is not a given for any application. Instead, depending on the application, e.g., of a next product generation, and the number of units, the desirable degree of integration on different levels must be defined, for example using representations as suggested in **Fig. 22**. Gaps between

the (application-specific) desired degree of integration and the current maturity point towards the need for research and development.

B. Challenges and Opportunities for Academic Research

Industry has demonstrated highly integrated converter building blocks up into the 10s of kilowatts power range, which feature power densities that are an order of magnitude higher than what with can be achieved with conventional (discrete) assembly technology.

In many applications, integration in the “classical” sense focusing on packaging and manufacturing is mandatory. This trend of shrinking the functional volume of a certain power conversion functionality is continuing further towards monolithic integration, e.g., in the form of GaN power ICs. This reduction in size comes with an increase in loss density and hence the need to improve power conversion efficiency and/or to improve the cooling technology, i.e., to reduce the thermal impedance between heat source and the ambient medium, e.g., by using advanced microchannel cooling [121]. Note that these are similar challenges as arise for today’s high-performance graphics processing units (GPUs). Clearly, there is a need for further research in this direction, and for clarifying benefits and according shifts of performance limits when new materials etc. become available.

However, these trends towards ever-more specific packaging and/or monolithic integration lead to a potential gap between university research capability and industry needs, as universities typically do not have in-house access to the latest packaging and manufacturing technologies nor the associated expertise; the realization of industry-like prototypes may no longer be possible without close industry partnerships. Such “fab-less” academic power electronics research [122], first, depends to a significant extent on, e.g., design tools and expertise provided by technology/manufacturing partners, and, second, is bound to result in highly specialized and highly focused PhD graduate profiles unlike today’s typical “T-shaped” profiles⁹ of power electronics engineers.

On the other hand, integration opens new opportunities for university research. First, as we have outlined in this paper, integration has many more facets that are *not* manufacturing/packaging-driven and hence will remain accessible; an example is the current high research interest in single-stage power conversion. However, whereas a myriad of topology variants etc. do exist and can be analyzed, only those concepts that can not only handle ideal but also non-standard operating conditions have the potential for ultimately achieving industrial relevance, narrowing down the space for relevant research.

Second, high degrees of hardware integration require new design methods and modeling techniques; this has already been mentioned 20 years ago in [12] but is still not an everyday reality. The close integration of different hardware components and building blocks implies the need for *co-design* across all

involved domains [124] such as electromagnetic, mechanical, thermal, manufacturing, reliability, and even software/control. This need is accentuated by interaction effects like the impact of external mechanical pressure (e.g., from a packaging process) on the losses of ferrite magnetic cores [125].

However, successful power electronics integration depends on more than having integrated design tools available. The success of future major integration initiatives depends on having an engineering workforce available that is educated and trained to address and embrace the multi-physics, multi-disciplinary design challenges that are critical to the success of any major integration project. A strong case can be made that today’s university power electronics education is too focused on individual engineering disciplines (generating “I-shaped” rather than “T-shaped” graduates) to adequately prepare future engineers in this field to grapple with the daunting cross-disciplinary challenges that they will face during major integration initiatives. Success will require re-thinking power electronics education for future generations of engineers in this field to prepare them for the challenging integration engineering problems that they will face in a world where power electronics integration becomes a more dominant theme in tomorrow’s products.

Once a design is realized as an ultra-compact integrated hardware demonstrator, the next challenge lies in testing: In contrast to conventional systems built using discrete components, typically only terminal waveforms are accessible for measurements, whereas inner functions cannot be directly verified using external measurement devices. There are two possible approaches to address this challenge, both highly interesting avenues for future university research. The first option is the integration of sensing functionality (voltage, current, etc.) into the hardware systems; possibly only for prototype testing and qualification but not in the series product, where, e.g., a certain degree of self-testing capability might result in a more favorable cost-benefit trade-off. The second option targets the convergence of design, simulation, and measurement tools, i.e., augmented reality oscilloscopes, where inner voltages/currents/temperatures are simulated and/or estimated, possibly using artificial intelligence (AI) and machine learning (ML) methods, based on measured terminal signals and displayed simultaneously [126]. To do so, future design processes should not only result in hardware demonstrators but also digital representations thereof, i.e., in digital twins (DTs). The DT parameters are online-tuned to best fit the measured (terminal) waveforms, and inner quantities are reconstructed from the DT. Beyond this application in testing, accurate DTs can be used for further tasks such as preemptive maintenance [127]. Thus, a certain shift of integration efforts from the hardware to the software domain is becoming apparent, relying on sensors (e.g., integrating various measurements such as temperature, vibrations, magnetic fields, and ultrasound noise with a wireless IIOT interface [128]) and increasingly sophisticated AI/ML-based modeling techniques to, e.g., maximize the utilization of existing systems while respecting operational and thermal limits—this shift clearly offers many highly interesting avenues for research.

All in all, the wide range of integration opportunities discussed in this paper, on different levels and in the hardware

⁹An engineer/researcher with a “T-shaped” skills profile combines deep technical expertise in a specific area with a broad knowledge covering a wide range of other subjects [123].

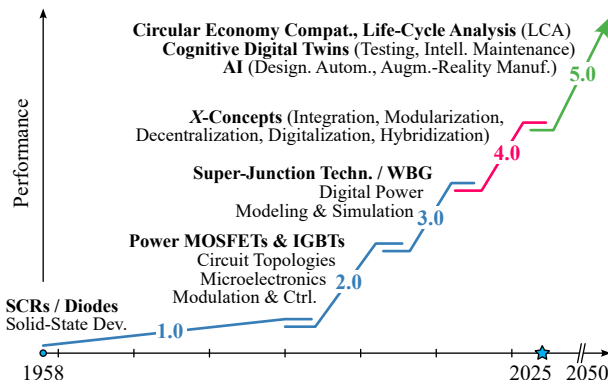


Fig. 23. Technology S-curves of power electronics as a superposition of individual S-curves. Historically driven by new power semiconductor technologies and last by the X-Concepts discussed herein, the next development cycle, i.e., Power Electronics 5.0, focuses on the need to consider life-cycle environmental impacts as new KPIs in all design processes. Figure based on [119].

as well as in the software domain, imply the existence of a high number of concepts that must be further evaluated in research to identify the (application-specific) optimum solutions in the sense of the “Integration Trilemma” from Fig. 21).

Finally, Fig. 23 shows the technology S-curve of power electronics, which in itself is an aggregate of individual S-curves. Historically, power electronics was mostly internally driven by, e.g., new power semiconductors or new circuit topologies, reaching maturity many years ago [15]. The most recent of the sub-S-curves was then dominated by X-Concepts, especially by integration. We expect the next one, i.e., Power Electronics 5.0, to be dominated by the need for taking into account as new set of key performance indicators (KPIs) like circularity, environmental impacts, sustainability, and integrating life-cycle assessment thinking into the design processes [119]—especially for highly integrated converter systems (see the “Integration Trilemma” in Fig. 21). Furthermore, the need to reshape our energy system into a multi-carrier energy system, including the de-fossilization of hard-to-abate sectors like long-haul transportation or the production of steel, cement and chemicals, creates immense opportunities for new applications of power electronics, i.e., business cases for industry [129], and fascinating research vectors for academia [130].

V. CONCLUSION

Integration has been and is a major driver of innovation in power electronics, together with the four other X-Concepts (modularization, decentralization, digitalization, hybridization). So far, the focus lay mostly on increasing power density of building blocks, essentially by means of advanced packaging and manufacturing technologies. In this paper, we have introduced a broader perspective, showing how integration is employed across all hierarchical levels of power electronics functional elements and units (materials, components, building blocks, converters, systems, and systems of systems), and involves the hardware as well as the software and control domains.

Whereas academic research targeting classical integration topics dominated by packaging technologies might be limited to a certain extent by technology access constraints, new

research opportunities arise regarding integration on other hierarchical levels and/or in the software domain, new co-design tools considering the interactions between electromagnetic, mechanical, thermal, etc. aspects, and testing/qualification of ultra-compact systems by means of either integrated sensing or augmented-reality oscilloscopes running digital twins to estimate non-accessible inner quantities from measured terminal waveforms.

Considering benefits and barriers of integration concepts in this broadened scope indicates that more integration is not necessarily always better: The optimum degree of integration on each hierarchical level is application-specific and evolves over time with technological progress. Finally, an optimum degree of integration is necessarily the result of a trade-off analysis between technological, economic, and environmental performance, as summarized in the described “Integration Trilemma”. The environmental performance, e.g., the ease of dismantability and material separation at the end of life, is of very high relevance in the context of Power Electronics 5.0, i.e., the next power electronics development cycle aiming at the implementation of integration and/or the X-Concepts in an environmentally compatible way.

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