Power Electronics System Integration for Electric and Hybrid Vehicles
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Abstract
The paper gives an overview of the basic requirements, concepts, and trends regarding a system integration of power electronics in hybrid (HEV) and electric vehicles (EV). A site-of-action system integration of the various power electronics subsystems minimizes costs and construction space requirements. New technologies that foster a system integration of power electronics and a merging with the mechanical environment are presented. The focus is on power modules and passive components.

1. Introduction
Miniaturization and system integration in power electronics are mainly driven by applications with severe installation space restrictions like automotive and robotics. In the past, the term "system integration" was mainly looked from the aspect of a higher integration of the power electronic system itself ([1] - [3]). A lot of fundamental concepts, technologies and pioneering solutions aiming on very high power densities were developed within the last 20 years.

In view of a further system cost and package volume reduction it is now necessary to think about a merging of the power electronics with its mechanical environment. Sometimes this is denoted as mechatronic system integration or simply as mechatronics. Besides many technical aspects, the movings within the value chain represent a great challenge in this process. This is because traditionally defined interfaces between electronic device and power module manufacturers, electronics assemblers, and the metalworking industry will blur or disappear.

However, the pressure to go this path increases. If one thinks, e.g., about a hybrid drive as an upgrade option for conventional passenger cars, one is directly faced with the lack of construction space as one of the most serious problems.

Future hybrid and all-electric vehicles will - apart from some micro hybrids - require a high voltage (HV) power net in addition to the conventional 14 V net. This high-voltage power net includes at least an electrical energy storage and a single drive inverter. Most different vehicle concepts exist that comprise further power electronic subsystems connected to the high voltage bus, like e.g. a DC/DC converter for supplying the low-voltage power net (as a replacement of the conventional 14 V generator), an inverter for an electric climate compressor, a DC/DC converter for stabilizing the traction bus voltage, or a AC/DC converter as an uni- or bidirectional vehicle to grid interface (s. Fig. 1). The high-voltage power net must be galvanically isolated against the low-voltage net and the vehicle chassis on safety reasons, and the HV harness generally requires shielded cables and connectors.

2. System Partitioning
Considering the various power electronic subsystems necessary in EVs or HEVs, the question arises how to set-up and/or integrate these subsystems, i.e. how to partition the whole system. Many options exist with respect to this. The most common solution today is to integrate all the power electronics in a central box. The advantage of a comparatively simple set-up is contrasted with the disadvantage of a separate expensive housing that is quite bulky and thus difficult to integrate in the engine compartment of existing passenger cars. Another decisive disadvantage is that a lot of expensive shielded high-voltage connectors and cables are necessary from the box to all of the various loads!

An alternative partitioning is shown in Fig. 2. This arrangement follows the basic idea of a "site-of-action integration" and minimizes the high voltage cable harness. Each drive inverter is integrated into or attached to the electric motor it operates. Any converter necessary for electrical energy management, power supply or charging is integrated into the energy storage that becomes a smart battery unit by this way.

Apart from the high voltage battery cable, there are no needless cable feedthroughs out of EMI-shielded housings.
in this case. The EMI filter effort is reduced to the unavoidable one at the interfaces from the isolated HV power net to the unshielded environment (e.g. to the 14 V power net or the AC grid).

3. System Integration

Major challenges regarding a site-of-action integration of power electronics arise from the fact that the available installation space is often very small, complex structured, and contaminated; high thermal and mechanical stress frequently add. The installation space is usually predefined by mechanical requirements with no consideration on power electronics needs.

A mechatronic system integration, therefore, requires more than just increasing the power density. Innovative integration concepts are necessary as well as new device, inter-connection, and cooling technologies that foster a 3D integration, increase the ruggedness, and decrease the costs of power electronics. A focus must be turned towards the passive components, especially towards the big passives like dc-link capacitors, converter chokes and EMI filters. Size reduction, higher structural flexibility, and an extended temperature range are prerequisites here to meet the challenges of a system integration.

Frequent arguments against a system integration are the aggravated service and an alleged lack of modularity. Regarding maintainability, there is no doubt that in future car workshops will repair power electronics just as little as a gear-box today. The power electronics must simply survive a whole vehicle lifetime with a failure rate close to zero. Of course a lot of research is still necessary to reach this target. Add-on solutions are a compromise regarding maintainability which nevertheless permit to benefit from most advantages of a deep system integration (s. Fig. 5).

Regarding modularity, there are several examples, e.g. the ECPE hybrid drive demonstrator [4], that have shown that modularity and system integration don’t exclude each other. Also in the case of a system integration, it is generally possible to structure the power electronics into modular building blocks. With a well thought-out design of these basic building blocks, adaptations to different power levels or construction volume geometries (e.g. different e-motor diameters) are possible quite easy without redesigning the whole power electronics.

Generally, cost reduction is the dominant development target. If one looks at the parameters cost, size, weight, and efficiency of power electronics more detailed, it becomes obvious that beside the power semiconductors also the necessary cooling measures and interconnections, as well as the passive components are of outstanding importance (s. Fig. 3). Some of these aspects are examined in the following more closely.

3.1. Power Modules and Cooling

Despite the fact that modern power semiconductors make it possible to convert electrical power with superior efficiencies, a highly effective cooling is indispensable. At an output power of 100 kW, e.g., 3 kW of losses arise even with 97% conversion efficiency, and these losses concentrate on chip areas getting smaller and smaller. This leads to extremely high heat flux densities, not only in the power...
semiconductors but also along the whole thermal path from the chips to the coolant. A careful optimization of the thermal path is indispensable therefore, especially under consideration of system costs, lifetime, and reliability. This optimization must include a careful selection of the involved materials especially with regard to their thermal expansion (CTE). Otherwise the thermal cycles during operation will result in undue thermo-mechanical stress that premature fatigues the setup. Ceramic substrate materials like alumina (Al₂O₃), aluminum nitride (AlN), or silicon nitride (Si₃N₄) are used for highest thermal performance. The ceramics are directly bonded or brazed to Al or Cu layers resulting in double-sided metallized substrates.

Traditional power modules are realized by bonding one or several substrates on a baseplate made of e.g. Cu or AlSiC. This leads to a mechanical robust device that is easy to handle for the user. The prefabricated modules have to be screwed on a cold-plate in which the non-bonded, mechanically detachable contact plane requires a thermal interface material (TIM) for acceptable thermal properties (s. Fig. 4 top). But even with the best available TIMs, this contact plane causes a considerable contribution to the total thermal resistance between chip and coolant. The non-optimum thermal performance in addition to a possible long-term degradation of the TIM layer, and several sensitive assembly steps (e.g. the well-defined high quality TIM application) make this module design not a real option for high volume automotive applications - especially when system integration is demanded.

Modules with a directly cooled baseplate, as shown in the center of Fig. 4, avoid the disadvantages of a TIM layer.

For an optimum heat transfer to the coolant, the surface area can be increased by plate fins or pin fins, open celled metal foam or the like. The geometry of the heat transfer structure has to be individually designed according to the physical properties of the coolant (water/glycol, oil or air), and the pressure drop vs. volume flow rate specification of the cooling circuit.

An even more far-reaching approach for directly cooled power modules does without a solid baseplate, and thus avoids the difficulties of a CTE adaptation between baseplate and substrate (Fig. 4 bottom). The extended backside metallization of the substrate provides the mechanical fixing and the sealing against the cooling circuit in this case [5]. Extensive pressure cycling and thermal cycling tests have proven the feasibility of this approach.

Fig. 5 depicts a system integrated power electronics based on such directly cooled substrates. Six substrates, each realizing an IGBT half-bridge (600V, 200A), are integrated into a two motor axle drive (Note: three of the substrates are located below the common DC link capacitor and thus not visible on the photo in Fig. 5). The photo shows three different assembly levels of the modules: the open cooling channel (right), the inserted directly cooled substrate (center), and the module with gate drive unit (left).

One option to attain a good heat transfer from the plane substrate to the coolant is a suitable designed turbulence body in the cooling channel, e.g. according to the ShowerPower™ principle [7]. Such a body can be a low-cost injection molded plastic part.

The necessity of a sealing against the coolant circuit can be completely avoided by bonding the substrates directly on water-cooled system components. This is a further major step towards system integration at which clear interfaces between the power electronics and mechanics disappear (mechatronics). The elimination of seals and screws leads to considerable space savings. Application examples are shown in Fig. 6.
The local metallization necessary for soldering or sintering the substrates, e.g. on an aluminum housing, can be realized chemically, by electroplating or by means of plasma or cold gas spraying.

Such high levels of system integration offer great potentials towards cost reduction and very high power densities, but also require high production volumes for cost effectiveness and a re-definition of the value chain.

The main failure mechanisms in power modules are the fatigue of solder joints, wire bonds, and substrates. Higher temperatures and increasing temperature swings reduce the time to failure dramatically. This sets narrow limits today to the usage of the properties of new wide bandgap semiconductors like GaN or SiC, which basically permit considerably higher chip temperatures than Si. Since the chip area necessary for a certain required current decreases with increasing maximum junction temperature, higher chip temperatures would be an important lever for the economically viable use of wide bandgap power semiconductors compared to Si power semiconductors with their much lower area costs.

Let’s assume a full-electric vehicle, operated only in urban traffic with one heavy acceleration or recuperation each 200 meters. This results in about 1 million active power cycles over a vehicle life of 200,000 kilometers.

In view of a corresponding life time specification, traditional power module technologies permit active temperature cycles with an amplitude of only 40 to 50 Kelvin. Since the cooling circuit in future electric vehicles will not be operated at temperature levels above 70°C, maximum junction temperatures in the range of 120°C would result. This is far below the maximum junction temperature of modern silicon power semiconductors and shows that the today available chip bonding and interconnection technologies are a real serious bottleneck.

The current research on improving the temperature cycling capability is mainly focussed on the replacement of conventional solder joints (e.g. by sintering [11], [12]), wireless chip interconnection technologies, and improved substrate metallizations.

According to Fig. 3, the power semiconductors, their interconnections and cooling cause about 50% of the material costs of an inverter. An important option for reducing these costs – beside the discussed increase of the maximum chip temperature – is an improved cooling. This also allows a reduction of the chip size for a given output current. Fig. 7 shows, as an example, the total chip area (IGBT plus diode area) needed for a 70 kVA inverter as a function of the DC link voltage and for two different chip area related thermal resistances (chip – coolant). This diagram is calculated under consideration of the static and dynamic semiconductor properties, under the assumption of an active chip temperature amplitude of 40 K, and a switching frequency of 10 kHz [9]. Note that in general a reduction in chip area walks along with a reduction of the substrate and heatsink area (and costs) too.

Typical values of the chip area specific thermal resistance achievable with different basic module designs are shown in Fig. 8. A value of 0.4 Kcm²/W is quite easy to attain with a directly cooled baseplate, whereas values in the range of 0.2 Kcm²/W and below generally require a double-sided cooling.

Various power module designs aiming on a pseudo or true double-sided chip cooling have been published in the last years (e.g. [13] - [21]). All till now known solutions show,
However, considerable limitations and drawbacks with respect to a system integration: Most concepts require an expensive and voluminous mechanical pressure fixture with sufficient spring excursion to avoid excessive stress in the mechanically overdefined construction (see Fig. 9, top and bottom). With the necessity of use of thermal interface materials a considerable part of the advantage of a double-sided cooling is wrecked again with these designs. High inert masses at both sides of the chip-substrate stack can result in unacceptable mechanical stress in the case of vibrational load (Fig. 9, center).

The basic requirements on an optimum power module design can be summarized as follows:
- a true double-sided cooling,
- a high power cycling capability,
- for that a lowest number of different materials,
- a minimum mounting overhead on system level,
- no additional exogenous mechanical stress, and
- cost effectiveness.

A minimum mounting overhead is an indispensable prerequisite for high power density and system integrability. Today’s situation that a power module with a water-cooled cold-plate requires a total height of at least one inch - and that only for interconnecting and cooling a power semiconductor chip of 70 µm height - is not acceptable in the long run.

A module concept with the potential to fulfill all the above-mentioned requirements is the “slot-module”, presented first in [22] and [23]. The basic structure comprises a sandwich of two DBC substrates with the active elements (IGBTs, Diodes or MOSFETs) in between (s. Fig. 10). The main innovations regarding a minimization of mechanical stress and mounting overhead are the surrounding of the sandwich with only a thin metal foil for gas-tightness against the coolant (water/glycol, oil, etc.), and the kind of insertion in the cooling channel “like a PC card”.

Several advanced solutions that even avoid the interface between the metal envelope and the substrate sandwich are described in [24]. These solutions also avoid all the problems of a solid metal envelope as described in [25].

An effective cooling of the plane slot-module surfaces is possible by, e.g., suitable turbulence bodies in the cooling channel as described before.

Up to now, the slot module is still in an early prototype phase. The main challenges that have to be solved are a highly reliable chip joining and sandwich assembly technology, a low mechanical stress design for the electrical terminals, and the proof of reliability.
3.2. Passive Components

Passive components contribute to cost and size of power electronic systems on a considerable scale (s. Fig. 3). Especially the capacitors necessary to provide a low-impedance DC link and to comply with EMI limits cause an essential share.

In the case of three-phase sine-modulated drive inverters the need for DC link capacitance could be reduced down to values of typically 7 to 10 µF per kVA inverter power (@ about 400 V) by means of a continuous improvement of the capacitor properties (low ESR), of the EMI filter design, and the inverter control loop performance. For the drive inverter in an electric passenger car this corresponds to a necessary capacitance in the range of 1.000 to 2.000 µF, with a voltage rating of typically 400 to 600 V, and an AC current rating in the range of 100 to 200 A, depending on the rated traction power.

Three main capacitor technologies are available today for realizing such a capacitance: multi-layer ceramic, metalized polymer films, and Al electrolyte.

Multi-Layer Ceramic Capacitors (MLCC) offer a small size, very high AC current ratings, and operating temperatures up to 200°C. Single components with values up to 40 µF/500 V are commercially available, the energy storage density is about 0,15 J/cm³. However, the high costs and mechanical sensitivity will handicap the use of these devices in high voltage automotive DC link applications in the foreseeable future.

Al electrolytic capacitors achieve the highest energy storage densities (up to about 1 J/cm³), but suffer from comparable high effective series resistances (ESR) or low AC current ratings. Unfortunately, there are narrow limitations regarding a reduction of the ESR, since the parameters nominal voltage, operating temperature range, and ESR can not be simultaneously optimized for chemico-physical reasons. For devices with a rated voltage above 350 volts, operating temperatures above 110°C are practicable only with considerable compromises. Moreover, capacitors with wet electrolyte show a strong increase of the ESR towards low temperatures, what can cause EMI problems in vehicles. The use of solid electrolytes has been successful only in components rated up to about 40 volts till now. The operating temperature range could be extended to 175°C with that or the series resistance reduced by more than an order of magnitude.

Polymer film capacitors show the greatest flexibility in device geometry among all capacitor technologies - even toroidal or coaxial capacitors are possible, and also amazing machining processes like the drilling of holes directly through the film stack. A ring-shaped device as shown in Fig. 11 was developed to provide the best usage of the available volume in an electric drive application; the contour of this device perfectly fits the typical geometry of an e-motor [4]. However, the large coefficients of thermal expansion (CTE) of the polymer film materials - and with that the comparably large dimensional changes of the whole capacitor with temperature - have to be considered and require innovative solutions with respect to the fixing, cooling, sealing, and the electrical connections of large-sized film capacitors.

The preferred film material for capacitors rated above about 250 volts is high purity biaxial oriented polypropylene (BOPP). This material allows a continuous operating temperature up to 100°C. Under consideration of a voltage derating an operating temperature up to 120°C is possible for a limited time. For the usage in applications with higher thermal load (e.g. in air-cooled electric wheel-hub drives with integrated inverter) also PEN films (up to 150°C) or PPS films (up to 175°C) are available - however, for considerably higher costs. Below 250 volts PET films become attractive since this material can be processed to thinner films and provides a higher relative permittivity compared to polypropylene.

It remains summarized to remark that polymer film capacitors provide today the most well balanced properties regarding the key parameters for automotive high voltage DC link applications, like ESR, temperature range, ruggedness, costs, etc.

Nevertheless, a DC link film capacitor with electrical values as defined before occupies a volume between one and two liters. This device is usually by far the largest component of an inverter and essentially determines the inverter volume. An increase of the energy storage density would therefore be the decisive lever for a reduction of the total inverter size. Other measures to reduce the passive components volume, which have proved to be very effective in DC-DC converters, like e.g. high switching frequencies and/or interleaved topologies [8], are unfortunately not effective in drive inverters.

The theoretical limit for the storable energy per volume in a dielectric with a maximum operating field strength $E_{max}$ and the relative permittivity $\varepsilon_r$ is given by:

$$
\text{Energy per volume} \leq \frac{\varepsilon_r E_{max}^2}{2} \, \text{J/cm}^3
$$
The corresponding values for various common dielectrics are shown in Fig. 12. Continuous operational fields are assumed for the given dielectrics and not theoretical breakdown fields. Note from this diagram that the energy storage density of polymer films is quite close that of high epsilon ceramics. The fact that available ferroelectrics cannot benefit from their high zero-field permittivity is a result of the very low operating field strength possible in MLCCs (because of the lack of any self-healing or self-clearance capability), and the dramatic decrease of the permittivity at high electric fields.

Energy densities up to 25 J/cm³ are reported from high epsilon (10...50) polymer films [26]. High performance dielectrics like Al₂O₃ or SiO₂ theoretically permit energy densities in the range of 10 J/cm³, which is about two orders of magnitude above that of commercial available capacitor devices.

Today Al electrolytic capacitors lose about one order of magnitude in energy storage density in the winding construction, because of the overhead necessary to achieve the self-healing property (note 1) in Fig. 12. The Al₂O₃ dielectric itself in el-caps is operated at about 500 V/µm. With a similar field strength the gate oxide (SiO₂) in each MOS-FET is loaded.

Supposed we would succeed in shifting the energy storage density of capacitor devices in the range of a few J/cm³ (while keeping all other parameters close to that of modern film capacitors), we would get a huge impact on the power density of power electronics. More research should be focused therefore on corresponding capacitor technologies; the perspective of a cost effective high volume production must be a central aspect in this development process.

The value of the DC link capacitance in many power electronic systems is defined by ripple voltage specifications at the DC input terminals. In this case, a DC link design with split-end capacitor and π-filter structure as shown in Fig. 13 is another approach to reduce the overall DC link volume and to improve the system integrability.

The following considerations shall make the effect on the overall DC link volume more obvious. The whole DC link occupies the volume:

\[ V_{ges} = V_{L1a} + V_{L1b} + V_{C1} + V_{C2} \]  

The volume share of the inductance is defined as

\[ k_{VL} = \frac{V_{L1a} + V_{L1b}}{V_{ges}} \]

A part “a” of the remaining volume shall be assigned to C₁ the rest is available for C₂

\[ V_{C1} = V_{ges} (1 - k_{VL}) a \]  
\[ V_{C2} = V_{ges} (1 - k_{VL})(1 - a) \]

Under consideration of the application specific maximum voltage and current ratings it is possible to define specific capacitance and inductance volumes. Both values depend on the respective device technology.

For the following investigations a specific capacitor volume of \( k_{Cu} = 1 \) cm³/µF, and a specific inductor volume of \( k_{Li} = 10 \) cm³/µH (@125 A) are assumed. This corresponds to the values of a state-of-the-art PP film technology (e.g. Epcos PCC, 450/500 V), and to chokes with ferrite cores.

With that the inductance and capacitance values that can be realized in assigned volumes are:

\[ L = \frac{V_L}{k_{Li}} \]  
\[ C = \frac{V_C}{k_{Cu}} \]

The corner frequency of the low-pass L₁/C₂ can now be written as:

\[ \omega_{c} = \frac{1}{\sqrt{L C}} \]
\[ \omega_0 = \frac{1}{V_{\text{ges}}} \sqrt{\frac{k_{L1} \cdot k_{C_1}}{k_{VL} (1-k_{VL})(1-a)}} \]  

(8)

An important observation from this equation is that the lowest corner frequency is always attained if 50% of the total available volume is assigned to the inductor \((k_{VL} = 0.5)\) - independent (!) of the inductor and capacitor device technologies.

The overall attenuation of the DC link can be described using the transfer impedance

\[ Z_{21}(\omega) = \frac{V_2(\omega)}{I_{\text{inv}}(\omega)} \]

(9)

that gives the voltage amplitude at the inverter terminals depending on the input current, i.e. the noise current sourced from the inverter stage. A minimum in the transfer impedance corresponds to a minimum voltage noise at the DC terminals at a given inverter current amplitude.

In Fig. 14 the transfer impedance is given as a function of the volume shares for a frequency of 8 kHz; the total DC link volume is 600 cm\(^3\). The DC link was loaded for these calculations with the battery and the DC cables \((L_{\text{cab1}} = 2.5\, \mu\text{H}, R_i = 0.4\, \text{Ohm})\). A minimum transfer impedance of 0.01 V/A means that an input current of 100 A\(_{\text{rms}}\) (at 8 kHz) would cause a terminal voltage noise of 1V\(_{\text{rms}}\).

Also in this case there is an optimum in the volume partitioning at \(a = 0.5 \text{ and } k_{VL} \approx 0.3\) – independent of the individual device technology and nearly independent of the load!

More detailed investigations show that the total DC link volume can be more than halved this way for a given terminal voltage noise. The practicable reduction depends on further aspects like the maximum AC current of the capacitor \(C_1\) or the location of the filter resonances in relation to the switching frequency.

A free assignment of partial volumes to inductive or capacitive components is, however, only usefully possible when corresponding device technologies, which provide a high structural flexibility, are available. An alternating line up of inductive and capacitive elements, a basic principle in electrical power converters, becomes possible then with lowest dead volume. A possible arrangement is shown in Fig. 15. Such arrangements not only provide highest volume efficiency, they also fulfill the requirements regarding mechanical ruggedness, low circuit parasitics, and highly efficient cooling [8].

Fig. 15 Narrow stacked arrangements of flat capacitive and inductive elements achieve highest power densities.

An effective heat transfer out of passive components is crucial for high power densities. The AC current rating of capacitors, e.g., is strongly depending on the cooling conditions. The better the cooling of a capacitor the smaller it can be for a given AC load.

Passive components generally consist of materials with a poor thermal conductivity like polymers or ferrites. An effective heat transfer out of volumes of such materials requires large heat conducting cross-sectional areas and short heat paths. This inevitably leads to a layer structure, normally an arrangement of planar layers (e.g. like in Fig. 15).

Whereas film capacitors provide the necessary structural flexibility, the situation is less ideal in the case of inductive components. Although the widespread planar inductors are a great step in the right direction, this approach reaches its limits as soon as the available construction volume is not cubic, but e.g. cylindrical or a toroid [4].
A new approach that provides the necessary high structural freedom are polymer bonded soft magnetics. Highly flexible and productive polymer processes like e.g. injection molding open new options for the realization of inductive devices, this especially applies in combination with sheet metal stamping techniques.

The magnetic properties of these core materials can be adjusted via the kind, shape, and volume percentage of the filler particles. The matrix polymer can be chosen of a wide spectrum of low-cost to high-performance polymers according to polymer processing and application requirements.

The specific properties of silicon iron – a high saturation flux density, relatively high RF losses, and low cost – recommend this material for EMI filter applications. Fig. 16 depicts the attainable permeability values as a function of frequency and filler content [27].

With filler contents above about 60 vol.% the relative permeability reaches values, which are comparable with the ones that can be found in conventional chokes designed for high DC bias currents. The distributed air-gap in polymer bonded soft magnets, however, generally causes much less stray field problems than the concentrated air-gap in conventional cores.

Sheet metal stamped bus-bars are widely used in high current power electronics. As outlined schematically in Fig. 18, a high degree of passive component integration is possible by a sectional molding of such leadframes in soft magnetic polymers. The high number of junctions and interconnections that is inevitable in conventional solutions with discrete capacitors and inductors can be greatly reduced this way. Moreover, further functionalities like housing, sealing, mechanical fixing, heat transfer, or feed-throughs can be realized by using the various possibilities of modern polymer processing technologies.

Fig. 17 depicts an EMI filter choke realized by molding a Cu winding in a thermosetting epoxy resin which was filled with 60 vol.% of FeSi6.8 powder. The choke shows an inductance of 5.5 µH at a bias current of 125 A and a very favourable soft saturation characteristic. The RF losses of the core material provide a nice damping characteristic that minimizes EMI filter ringing without deteriorating the DC performance.

The fact that the contour of this choke could be perfectly adapted to the given construction space, a gear-box housing, was a prerequisite here for a system integration of the EMI filter [4]. Thermosetting resins allow both very high filler contents and low processing temperatures that are compatible to other electronic components like film capacitors or PC boards - another important aspect with a view to system integration.

4. Conclusions

System integration of power electronics is inevitable to fulfill the cost and package volume requirements on future hybrid and all-electric passenger cars.

New technologies emerge which may greatly improve power density and system integrability.

The optimization of a power electronic vehicle component always requires a comprehensive survey of the whole drivetrain.
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6. Literature


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