

Integration technologies for high power density power electronic converters for AC drives

J. Popović*, J. A. Ferreira**, M. B. Gerber**, A. König***, R. de Doncker***

* European Center for Power Electronics (ECPE), Landgrabenstrasse 94, D-90443 Nuremberg (*Germany*)

** Delft University of Technology, Mekelweg 4, 2628 CD Delft (*The Netherlands*)

*** RWTH-Aachen, ISEA, Jaegerstrasse 17-19, D-52066 Aachen (*Germany*)

Abstract— It is widely recognized that significant energy savings could be expected through a widespread use of variable speed drives in motor driven systems. In order to widely implement this concept, the size and cost of the power electronics in drives are the key factors. One of the demonstrator programs of European Center for Power Electronics (ECPE) is focussing on achieving high power densities in converters for AC drives in the power range of a few kilowatts. The general approach in the program is based on two concepts – integration and advanced thermal management. This paper focuses on the integration technologies aspect of this program. State-of-the-art commercially available converters in AC drives are constructed by using similar technologies. In this paper some new technologies that can be used to construct high power density converters are presented. The benefits of these technologies when compared to conventional solutions, such as size, losses and cost are discussed.

Index Terms—AC motor drives, Packaging, Power electronics

I. INTRODUCTION

Power electronic converters in state-of-the-art industrial drives are implemented using similar technologies even though they come from different manufacturers. Power semiconductors in the bare die form, including an input diode rectifier and inverter switches, are mounted on a ceramic carrier such as Direct Copper Bonded (DBC) substrate, wire bonded to establish electrical interconnections and enclosed in a plastic housing. The bottom side of the module is mounted onto a heat sink for heat removal and the top side is connected to a PCB carrier, where the rest of the circuitry, including a DC-link filter, EMI filter, auxiliary power supplies and control circuitry is assembled. The passive filtering components in the assembly are bulky and not geometrically optimized to fit with each other. The volumetric utilization of such assemblies is poor – over 50% of the converter in commercial drives is occupied by air, which results in low power density converters.

The main objective of the demonstrator program “Industrial Drive – System Integration” of the European Centre for Power Electronics (ECPE) is to significantly reduce the size of the converter of a 2.2 kW industrial

drive for an asynchronous machine. Thereby, the development of the key technologies is focused on compact design, manufacturability and costs. The demonstrator program is being carried out by two competence centres: Delft University of Technology and RWTH Aachen.

In this paper, we present an overview of new technologies that can be used to construct high power density converters for ac drives. The benefits of these technologies when compared to conventional solutions, such as size, losses, power density and cost, are discussed in the following text. Some of the presented technologies will be used in the demonstrator implementation.

II. HYBRID INTEGRATION OF POWER ELECTRONIC CONVERTERS IN INDUSTRIAL DRIVES

We envisage that the project objectives can be met by pursuing two concepts – advanced thermal management and integration. Advanced cooling is crucial for ensuring that, given a small volume, the heat dissipated by the components is removed efficiently so that the components operate in their allowed temperature range. Integration of components is a means to achieve a compact design, reduce the number of construction parts and thus decrease the cost [1].

Fig. 1 shows the circuit schematic of a typical power electronic converter in an ac drive. It can be noticed that the circuit consists of a large diversity of components, including power semiconductors for input rectifier and output inverter; large passive components for low frequency filtering and passive components for EMI filtering; a relay and resistor for inrush current limiting; low current, low voltage components for control circuitry, an auxiliary power supply, gate drives etc. These components perform different functions, handle different current and voltage levels and dissipate different amounts of heat, which makes monolithic integration, as seen in silicon integration in microelectronics, not feasible from the fundamental electromagnetic and cost viewpoints. Therefore, hybrid integration is the option of choice for integration in power electronic converters of this power range.

The circuit shown in Fig. 1 is partitioned according to the components characteristics such as heat density, maximum operating temperature, current/voltage level, operating frequencies etc. Each partition is manufactured

Financial support should be acknowledged here. Example: This work was supported by Italian Ministry of Research.

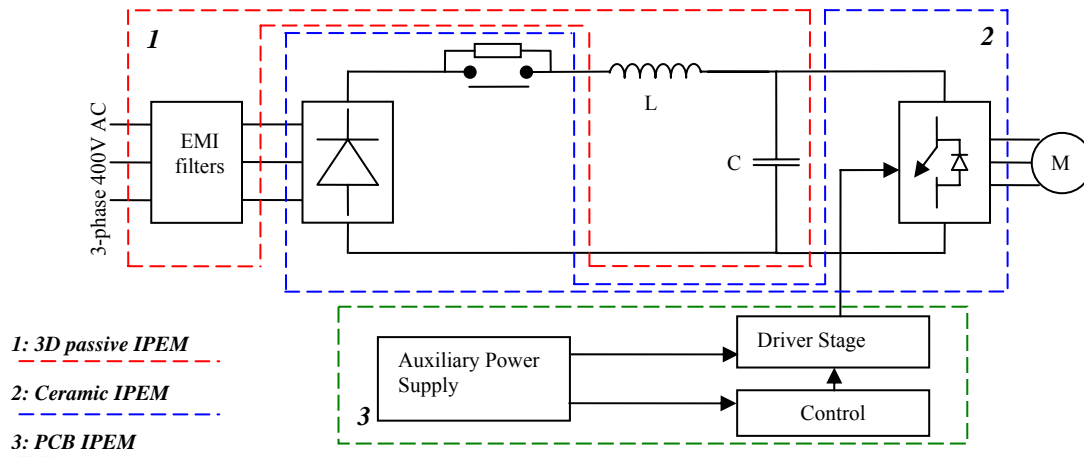


Fig. 1 Three IPEMs in the converter – circuit partitioning

using the most suitable integration technology and is referred to as Integrated Power Electronics Module (IPEM) [2].

The high heat density, high power semiconductors require heat spreaders and a high surface area to volume ratio to conduct and dissipate the heat. This implies the use of planar construction methods and highly thermally conductive carriers such as ceramic, as found in conventional power modules. These components form an IPEM referred to as the *Ceramic IPEM*. The low frequency filter components need to have a sufficient volume for energy storage. Furthermore, since heat densities are low and a smaller surface area to volume is required to conduct and dissipate the heat, a three dimensional construction method can be employed. These components referred to as the *3D Passive IPEM*. The components that make up the control circuitry, auxiliary power supplies and gate drive stage are low current, low voltage components and can be implemented in various low power technologies. Since PCB technology is the most widely used technology in this power range due to its maturity and cost-effectiveness, it will also be used in this project. The IPEM made out of these components is referred to as *PCB IPEM*.

The thermal management concept that will be pursued in this demonstrator program is based on an integrated housing (I-housing). This is an aluminium casing that encloses the three IPEM's and is forced air cooled using a fan. It serves as a heat collector and a heat sink for the three IPEMs. The overall shape and the texture/profiling of the surfaces will be designed so that the heat is removed in a way that the components of the IPEMs will operate at their desired temperatures. The I-housing concept and spatial arrangement of the three IPEMs are outside the scope of this paper.

III. TECHNOLOGIES FOR THE CERAMIC IPEM

As previously mentioned, power module technology utilizes bare die silicon power semiconductors assembled on a ceramic carrier, such as Direct Bonded Copper (DBC) substrates. We propose that the Ceramic IPEM is based on this packaging technology with the possibility

of using novel semiconductor technologies and integrating more functions into the power module.

A. Semiconductor technologies/Silicon Carbide (SiC)

In state-of-the-art industrial drives, the inverter is commonly implemented with IGBTs and anti-parallel freewheeling silicon diodes. Emerging Silicon Carbide (SiC) technology offers semiconductor switches with lower losses, higher voltage breakdown and ability to operate at higher temperatures which opens up new possibilities for design and construction of power electronics circuits. Due to lower losses and higher operating temperature, a smaller heat sink can be used compared to the heat sink needed for an inverter with IGBT devices, thus saving on size and system cost. The production costs of SiC devices is however still higher than those of silicon devices due to the technological demands for SiC crystals, available size of SiC wafers and lower yield.

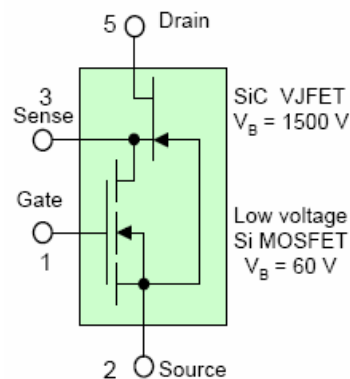


Fig. 2 Cascode SiC VJFET/SiMOSFET configuration [1]

Currently available devices manufactured in SiC technology are Schottky diodes and Vertical Junction FET (VJFET) transistors [3][4]. SiC Schottky diodes have no reverse recovery which is important knowing that reverse recovery losses make up a large percentage of total diode losses. Since JFETs are normally-on devices, a negative voltage has to be applied to the gate terminal in order to turn the device off. The voltage

needed to switch this device off is close to the minimum allowed gate voltage. Hence, JFETs require a very exact gate drive unit. To avoid a short circuit during turn-on of the inverter and to enable switching these devices with a standard gate drive unit, a low voltage MOSFET and JFET can be connected in a cascode configuration that is shown in Fig. 2. The cascode configuration can be driven with a standard gate driver and does not need a negative supply voltage. The switching and conduction losses in the low voltage MOSFET are low.

For the implementation of the inverter in the Ceramic IPEM, three options were investigated and compared to each other: an IGBT with an anti-parallel ultra-fast silicon diode, an IGBT with an anti-parallel SiC Schottky diode in one package [5] and a JFET cascode [3]. For the given circuit operating conditions, the power losses for all three options were calculated and are shown in Table I.

TABLE I
SEMICONDUCTOR SWITCH TECHNOLOGIES FOR INVERTER – COMPARISON

	IGBT/ Si diode	IGBT /SiC diode	JFET Cascode
Power loss [W]	12.28	7.53	11
Maximum junction temperature (T_j) [°C]	125	125	175
Maximum thermal resistance ($R_{th,case-ambient}$) [°C/W]	5	8.9	10.24

The maximum allowed thermal resistance from the device case to the ambient was also calculated taking into account the maximum operating junction temperature of the device and the assumed ambient temperature of 50 °C. It can be seen that the IGBT/SiC diode combination exhibits the lowest losses but due to the higher maximum operating temperature of the SiC VJFET, the required thermal resistance of the JFET cascode is lower, which implies that a smaller heat sink could be used. Furthermore, it can be concluded that both the IGBT/SiC diode and JFET cascode option outperform the conventional IGBT/Si diode option, both from power losses and maximum allowed thermal resistance viewpoints.

B. Inrush current limitation

Since the capacitor in the low frequency filter of the converter acts as a short circuit at the moment of connecting the converter to the grid, the inrush current would be very large without an additional circuitry for limiting this current. The standard topology of the inrush current limiting circuitry consists of a relay connected in parallel to a resistor, as shown in Fig. 1. The disadvantage of this topology is a large volume.

An alternative to this topology is to use a MOSFET to act as a switch to short circuit the resistor after the charge-up of the capacitor as illustrated in Fig. 3. This sub-circuit could be implemented as part of the Ceramic IPEM by mounting an additional MOSFET die on the DBC carrier of the Ceramic IPEM which occupies much less space and volume compared to the conventional topology. An option for implementing the resistor is to integrate it on the ceramic carrier by means of thick film technology.

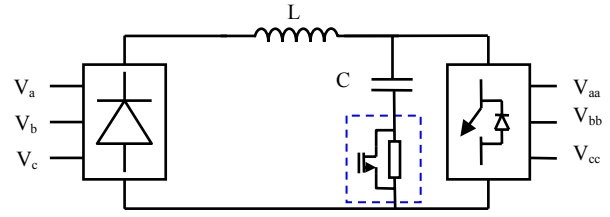


Fig. 3 Inrush current limitation with a MOSFET and resistor

C. Interconnections

One of the crucial issues in implementing the Ceramic IPEM is electrical interconnection techniques used. This includes both chip level interconnections and interconnections between the Ceramic IPEM and the rest of the converter. State-of-the-art power modules mostly use wire bond technology, where the bottom drain/collector electrode is soldered on the carrier while the connections from the top die surface to the carrier are performed by means of aluminium wire bonds. This is an established and mature technology. However, wire bonds are prone to detaching from the semiconductor die due to electrical and thermal fatigue which significantly affects the module's reliability. This vertical arrangement also limits the cooling of devices to only single-side cooling.

In order to deal with these issues, technologies that employ flip-chip solder joints instead of wire bonds are emerging, such as FlipFET [6], MOSFET BGA [7] and technologies that allow for double sided cooling such as DirectFET [6]. In Center for Power Electronics Systems (CPES) in USA a lot of research effort has been put in developing planar metallization technologies for interconnections of all power dies on the module level [8]. These technologies make use of metals on the planar surface of the substrate in the form of thin film, such as Embedded Power technology. Another alternative is pressure contacts, which is a contact realization method that is free of the internal stresses that are common to solder based interconnections. A pressure contact on the chip level is realised by replacing the solder bond with a direct bond between the semiconductors and copper conductors and maintaining the connection with an additional external pressure load. The advantage of the pressure contact is that there is a force only in the direction perpendicular to the semi-conductor. Pressure contacts in the form of springs are also used to interconnect the power module carrier to the rest of the circuitry mounted on a PCB [9] or in this case the Ceramic IPEM to the rest of the converter.

D. Additional possibilities

In addition to the technologies presented above, additional functions such as gate drives and decoupling capacitors could be integrated in the Ceramic IPEM by assembling gate drive dies and metallized ceramic tiles [10] or bare metal film capacitors such as SilverCaps [11] onto the DBC.

IV. TECHNOLOGIES FOR THE 3D PASSIVE IPEM

In conventional drives, low frequency and EMI filters are realized as assemblies of discrete components. These components are generally bulky and not designed to spatially fit with each other, which results in a large percentage of the converter volume being occupied by air.

A. Integrated LC technology

By using electromagnetic passive integration principles, inductive and capacitive passive components can be integrated into one component. This technology makes use of enhancing the capacitance in windings by inserting a dielectric layer between wound conductors [12]. Various technologies can be used to implement such structures, such as ceramic technology, polypropylene film and electrolytic capacitor technology [13]. Fig. 4 shows the basic structure of an integrated LC component. By connecting the structure in an appropriate manner, different circuit combinations can be achieved. By adding more layers with different dielectric and magnetic properties, more complicated structures (L-C-T, L-L-C-T etc.) can be realized. Planar electromagnetically integrated passive components in ceramic technology have been extensively analysed and applied to resonant and non-resonant converter circuits and integrated EMI filters [14][15].

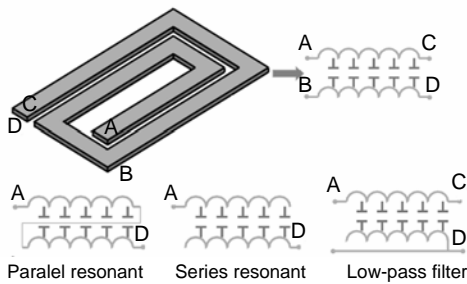


Fig. 4 Integrated LC - principle

As shown in Fig. 1, the 3D Passive IPEM consists of a low pass filter in the dc-link and an input EMI filter. In conventional drives, the DC link mostly consists of the capacitance only. By using LC integration, a DC link inductor could be integrated in the same component with the capacitor thus improving the total harmonic distortion (THD) of the input current. As high capacitance values are required for dc link capacitance, the preferred technology due to its high energy density is electrolytic capacitor technology. The inductor is implemented by utilizing the aluminium foils of the capacitor to implement the windings and a magnetic core that the foil windings are wound around (Fig. 5). As in a conventional electrolytic capacitor, the windings should be enclosed in a can, which would differ from a conventional can in that that there is a hole in the middle for the magnetic core, as shown in Fig. 5. The advantage of this technology is that a conventional electrolytic capacitor, which is typically a bulky component, can be replaced with a component that performs several functions.

The EMI filter from Fig. 1 can also be implemented

using the principle of electromagnetic integration. Reference [16] shows how an integrated EMI filter in planar ceramic technology could be designed in half the volume of the discrete benchmark and with significantly improved parasitic parameters, especially the equivalent parasitic capacitance of the common mode inductor which determines the high frequency behaviour of the filter.

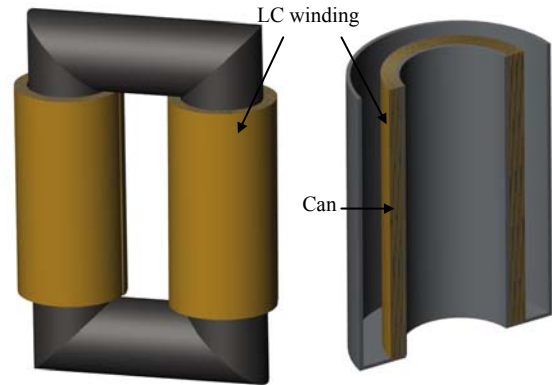


Fig. 5 LC in electrolytic capacitor technology

B. Alternative magnetic materials for EMI filters

EMI filters occupy a substantial portion of the total converter size, according to some estimations around 15% - 20%. The common mode choke represents a large part of this volume. Common mode chokes in commercial converters are mostly implemented by using ferrite cores. By using recent soft magnetic materials, such as amorphous and nanocrystalline, the volume of a common mode choke can be reduced to as high as half of the volume of the ferrite based choke (Fig. 7).

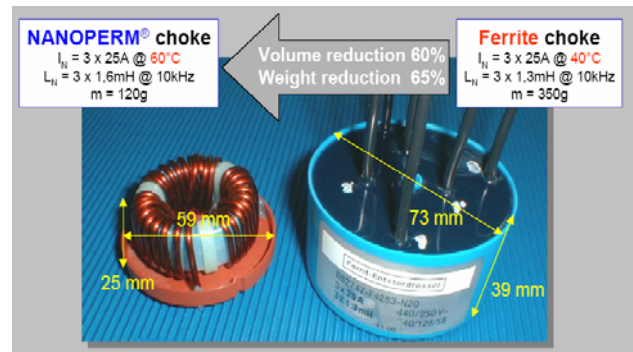


Fig. 6 Nanocrystalline vs. ferrite common mode choke volume ratio [17]

C. Multifunctional bus bar technology

The Ceramic IPEM and PCB IPEM use circuit carriers, DBC and PCB respectively, for the electrical interconnections, mechanical support and as part of their thermal management. Due to the three dimensional construction of the 3D Passive IPEM a three dimensional interconnection and support structure is a better option than a planar circuit carrier. One of technologies that allow for such an arrangement is laminated bus bar technology.

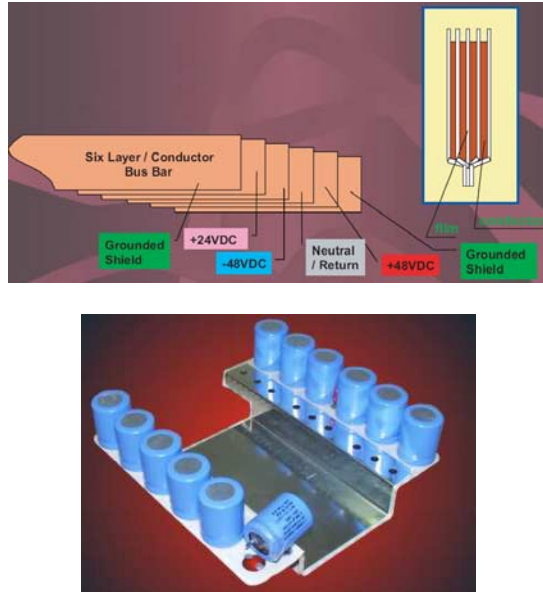


Fig. 7 Laminated bus bars a. principle [18] b. interconnection and support structure [19]

Laminated bus bars are made of layers of insulated copper sheet, where each layer is a conductor and can distribute power at a different voltage [18] (Fig. 7a). If sufficiently thick, bus bars can provide mechanical support for the components in the form of a metal carrier, as shown in Fig. 7b. The advantage of such an arrangement compared to the conventional practice of assembling passive components on the circuit PCB carrier is the possibility of spatially arranging the passive components in a 3D manner thus achieving a smaller volume of the passive component assembly. This will result in a reduction of the total converter volume and an increase in power density. Additionally, since bus bars are made of metal, they can also be used as thermal conductors, to conduct the heat dissipated by the components. Furthermore, the use of thin parallel conductors with a thin dielectric laminated together minimizes the effect of inductance on electrical circuits.

D. Rigid-flex PCB

Besides laminated bus bar technology which is particularly suited for high currents, for lower current levels PCB technology could also be used. The advantages of this technology are its maturity and cost-effectiveness but it is generally used for two dimensional arrangements. However, by using rigid PCB panels interconnected by flexible PCBs, three dimensional arrangements can be accommodated [20].

E. Pressure contacts

In Section III pressure contacts were discussed as a means for implementing chip level interconnections and the interconnections between the Ceramic IPeM and the rest of the converter. In order to expand the concept of using pressure contacts for electrical interconnections in power electronics assemblies, alternative ways of implementing pressure contacts should be explored. One alternative would be an arrangement where spring

contacts connect functional blocks (such as for e.g. bare metallised film capacitors) to circuit carriers. Taking this concept further one could envisage a power electronic assembly as a box that consists of unpackaged components or functional blocks that are electrically interconnected by means of pressure contacts. These components would have to be specially shaped in order to geometrically fit with each other. Mechanical design of such an assembly would require special attention.

V. TECHNOLOGIES FOR THE PCB IPeM

In order to suit the system integration concept and fit with the other two IPeMs, the PCB IPeM has to have a planar low profile. Knowing that passive components and heat sinks are generally the bulkiest components, one needs to look for technologies that allow for low profile passive components and advanced thermal management.

In conventional PCB assemblies, PCB is generally used only for electrical interconnections and mechanical support of components. Let us see how the PCB functionality can be increased in order to achieve the above mentioned characteristics of the PCB IPeM.

A. PCB embedded passive integration

Capacitive and magnetic components can be embedded into the PCB carrier by laminating layers of materials with enhanced dielectric or magnetic properties together with conventional PCB layers in the standard multilayer PCB manufacturing process [21]. In this manner, very low profile assemblies can be built. Capacitive laminates are commercially available and the capacitance per unit area ranges from 200 pF/cm² for laminates compatible with the standard multilayer process [22] to around 4.5 nF/cm² for very thin laminates that require a sequential build-up manufacturing process [23]. Given these values it can be concluded that large values of capacitance can not yet be implemented in this technology. As for embedding magnetic components, integrated windings are state-of-the-art. Magnetic laminates in the form of polymer like materials with ferrite powder are still in the research phase [22]. However, the materials available so far have high losses. Therefore, an alternative would be using low profile planar ferrite cores with windings integrated in the PCB metallization.

B. Heat spreading and thermal vias for better thermal management

As already mentioned, achieving a low profile of the PCB IPeM is necessary for the spatial arrangement of the IPeMs. For this reason, surface mount components should be used. The PCB functionality can be increased further by utilizing it for assisting the removal of the heat dissipated by the components. The PCB copper pads that the components are mounted on can be used to spread the heat dissipated by the components over a larger surface before it is conducted through the PCB. This is especially important taking into account the low thermal conductivity of conventional PCB (< 1 W/mK). Thermal vias through the PCB that are manufactured in the same

step as conventional electrical interconnection vias can be utilized to conduct the heat from the copper pad to the bottom surface of the PCB (Fig. 8). This surface can be used as a heat exchange surface if it is exposed to the air flow. Such an arrangement eliminates the need for extra assembly parts for heat sinking, which is advantageous both from the low profile and cost viewpoint.

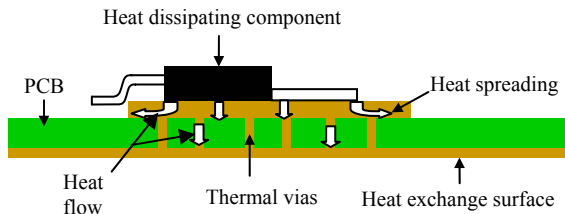


Fig. 8 PCB role in thermal management

VI. CONCLUSIONS

Several integration technologies that can be used to implement a high power density converter for ac drives in the power range of a few kilowatts are presented. The general approach to achieving high power densities is through hybrid integration in the form of Integrated Power Electronics Modules (IPEMs). The presented technologies are classified according to the IPEM that they will be used to construct. The benefits of these technologies such as size reduction and reduction of the number of components and assembly parts were discussed. Concerning cost, long term cost-effectiveness based on a large production volume should be considered since the production volume and learning curve are crucial factors, together with the intrinsic material and process cost of the technology. Furthermore, the system cost rather than the cost of individual components and parts should be considered during decision making.

In the case of the Ceramic IPEM, the key prospects lie in new semiconductor and interconnection technologies while in the PCB IPEM case the main opportunities are in technologies that allow for low profile passive components. The biggest challenge lies in establishing a new component and packaging technology base for the 3D passive IPEM as a system component, since this is a new concept unique to this demonstrator program.

REFERENCES

- [1] J. Popović, J.A. Ferreira, "An approach to deal with packaging in power electronics", in IEEE Transactions on Power Electronics, May 2005, Volume 20, Issue 3, Page(s): 550 – 557.
- [2] J. A. Ferreira, J. Popović "Towards new power electronic technologies for better packaging and higher levels on integration" 2005 CPES Power Electronics Conference, April 17-19 2005, VirginiaTech.
- [3] SiCED, www.siced.de
- [4] Cree, www.cree.com
- [5] Advanced Power Technology, www.advancepower.com
- [6] International Rectifier, www.irf.com
- [7] Fairchild Semiconductor, www.fairchildsemi.com
- [8] Liang, Z.; van Wyk, J.D.; Lee, F.C. "A chip-level process for power switching module integration and packaging"; Conference Record of the 39th IEEE Industry Applications

- Conference, Volume 3, 3-7 Oct. 2004 Page(s): 1932 – 1939
- [9] Semikron, www.semikron.com
- [10] BCESud, www.bcesud.com
- [11] EPCOS, www.epcos.com
- [12] M. Ehsani, O. H. Stielau, J. D. van Wyk, I. J. Pitel, "Integrated reactive components in power electronic circuits", in IEEE Transactions on Power Electronics, Volume: 8, Issue: 2, April 1993, Pages: 208 – 215.
- [13] S. J. Marais, J. A. Ferreira, J. D. van Wyk, "Integrated filters for switch-mode power supplies" Conference Record of the 1995 IEEE Industry Applications Conference, Thirtieth IAS Annual Meeting, 8-12 Oct. 1995, Volume 1, Page(s): 809 – 816.
- [14] Strydom, J.T.; van Wyk, J.D. "Volumetric limits of planar integrated resonant transformers: a 1 MHz case study"; IEEE Transactions on Power Electronics, Volume 18, Issue 1, Part 1, Jan. 2003 Page(s): 236 - 247
- [15] Rengang Chen; van Wyk, J.D.; Wang, S.; Odendaal, W.G.; "Planar electromagnetic integration technologies for integrated EMI filters" Conference Record of the 38th Industry Applications Conference, 12-16 Oct. 2003 Volume 3, Page(s):1582 – 1588.
- [16] Rengang Chen; van Wyk, J.D.; Shuo Wang; Odendaal, W.G.; "Improving the Characteristics of integrated EMI filters by embedded conductive layers" IEEE Transactions on Power Electronics, Volume 20, Issue 3, May 2005 Page(s): 611 – 619.
- [17] Magnetec, www.magnetec.de
- [18] FCI connectors and connecting systems, available at: http://www.fciconnect.com/pdf/brochures/950523-004_Bus_Bar.pdf
- [19] Eldre corporation, www.busbar.com
- [20] de Jong, E.C.W, Ferreira, J.A., Bauer, P. "3D Integration with PCB technology" Conference Proceedings of the Applied Power Electronics Conference (APEC), Dalas, USA, 19-23 March 2006.
- [21] Waffenschmidt, E.; Ferreira, J.A "Embedded passives integrated circuits for power converters" Power Electronics Specialists Conference, 2002. IEEE 33rd Annual, Volume: 1, 2002, Page(s): 12 -17.
- [22] Isola, www.isola.de
- [23] 3M, www.3m.com