G2E lab
Grenoble Génie Electrique
Grenoble Electrical Engineering

Energy efficiency oriented

Highlights

2014

Power Electronics

Grenoble INP
Université Joseph Fourier GRENOBLE
CNRS
lanef Laboratoire d'Alliances Nanosciences-Energies du Futur
INSTITUT CARNOT Energies du futur

Foreword

PE: Power Electronics

Power electronics has become the central interface for the control and conditioning of electrical energy at all power levels. Highlighted by the requirements of compactness of portable systems, this discipline is also strongly influenced by the context of energy savings, sustainable and green electronics. The introduction of non-conventional energy sources and storage, the need for ever-increasing electric mobility, combined with the flexibility and efficiency provided by static power converters have led to a proliferation of applications in industrial fields and consumer.

In this demanding environment where the desired performance are related to energy efficiency, electromagnetic standards and miniaturization, the Power Electronics team focused for the last ten years on upstream research activities. Among others, this research includes the technological and conceptual aspects, to propose new concepts and tools for future conversion systems. Thus, a major effort was made on the power integration, especially the monolithic and hybrid integrations to offer required breakthroughs in our field. This effort continued into the joint / coupled design approach of power semiconductor devices and their environment, breakthroughs in packaging, integrated or optimal cooling systems for power devices, and in the design of generic blocks and towards wide band gap devices. In conjunction with this guidance, the team is actively pursuing the development of modeling tools, while collaborating with the MAGE team in the view to better meeting the changing needs of design. This is of particular interest, especially since packaging and EMC / EMI are challenged by increased switching speeds and physical proximity of the new components.

Along with these upstream activities, the team wants to remain close to applications whose needs are driving innovation. The actions in this direction (CIFRE PhD funding and agreements, collaborative projects) focused on power conversion with a high added value such as uninterruptible power supplies, transportation and contactless energy transfer.

To achieve these objectives, the research is organized around three complementary areas:

- *Power semiconductor devices and integration: integrated functions, drivers, packaging and thermal management.*
- *Design of power converters and their valorization: Embedded systems in transportation, Uninterruptible Power Supplies...*
- *Electromagnetic modeling and design tools for passive components, systems and EMC.*

The organization of these areas is to ensure the proficiency of various aspects of a static power converter, from the component to its integration within the thermal and electromagnetic environment. The global system level constraints and control is being conducted in collaboration with the SYREL team at G2Elab. This desire to «coupled design» is more essential than ever introduced by the strong constraints facing our discipline but also by the advent of the wide band gap devices affecting all three research activities. From this perspective then, the team is particularly well positioned in terms of modeling tools (InCa, Flux, Cades, GOT) and technological means (CIME-Nanotech, CEA-LETI).

Contents

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Thermal management and characterization of power semiconductor devices

EP

The heat density dissipated by power semiconductor devices can reach several W.cm-2. Their thermal management is therefore an important issue in power electronic systems. Several studies are carried out in G2Elab: the improvement of the package by integrating the cooler in the power module or in the chip itself, and the improvement of the cooling system. The thermal characterization of power modules in on-line or off-line operation is based on adapted characterization methods which are also studied in the lab.

I. Integration of thermal functions in the power module

The heat transfers in a power module can be affected by modifying different elements:

- the thermal interfaces between the dies and the cooling fluid,
- the heat spreading material to increase the exchange surface.

Several studies dealing with these topics were carried out in the past. For example, we have realized and characterized power chips integrating cooling channels in their structure (figure 1). We also studied thermal spreaders based on the flow of a metal liquid in the power electronics substrate.

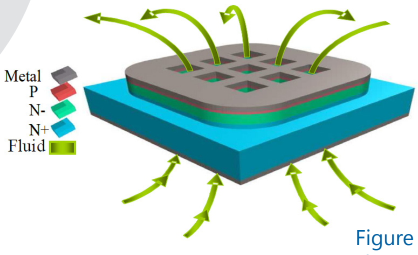

Figure 1: Integration of cooling channels perpendicular the PN junction in a power chip

II. Cooling systems

The power electronics team is interested in the use of non-conventional fluids. The main objective is to propose new cooling solutions to improve the convective heat transfer coefficient and to remove the mechanical pump when it is possible. The interest of the latter point is to improve the reliability of cooling equipments.

In the past, studies have been carried out on the use of liquid metals. Today, our work deals with the thermal characterization of ferrofluids under magnetic field (figure 2).

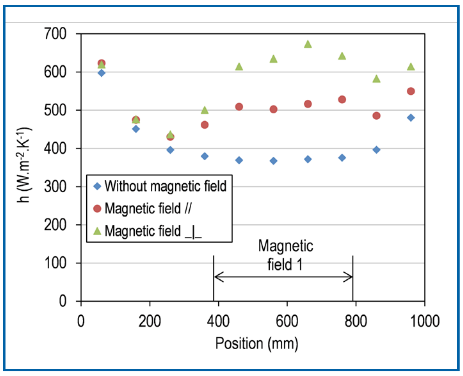

Figure 2: Improvement of the convective heat transfer coefficient in a square duct. Influence of the direction of the magnetic fluid.

III. Thermal characterization

The thermal characterization of power semiconductor devices and of their cooling system necessitates the knowledge of the junction temperature. It allows for the measurement of the thermal resistance/impedance in off-line conditions. The laboratory works on the elaboration of new thermo-sensitive electrical parameters and realizes thermal sensors directly integrated in the chip (figure 3). These works are made in collaboration with IFSTTAR/LTN.

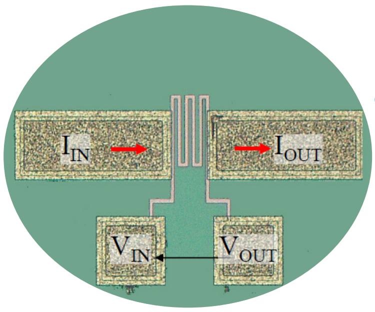

Figure 3: Thermal sensor integrated on the surface of a power diode

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Towards an autonomous, efficient and versatile power switch?

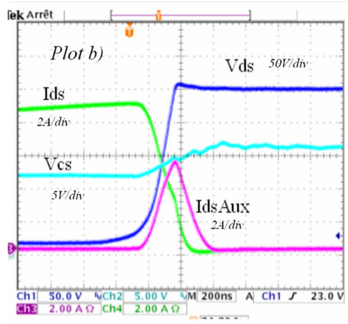
Although many efforts are currently focused on improving the intrinsic performances of the power semiconductor devices, it remains essential to ensure that this performance will be guaranteed once the components are placed in their environments (thermal, electromagnetic). While considering all the elements necessary for the power switch function, the functional integration offers efficient, versatile and easily controlled power switches. This generic approach allows using larger scale fabrication techniques.

• *Approach and main results*

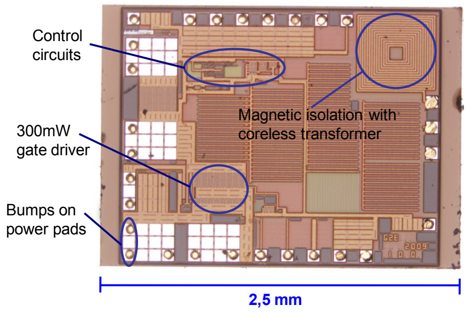
Heterogeneous functional integration taking advantage of each technology is a promising approach for improving reliability, cost and performances. It is based on a joint design approach of the power device and its electronic and physical environments for example a CMOS driver and a VMOS power switch associated one on top of the other. Both components share electrical interconnections and required functions. The VMOS based power device monolithically integrates several required functions for a self supply operation of the control chip. On the other hand, the CMOS chip integrates all the functions for controlling the power component. The electrical isolation is provided by a coreless transformer allowing isolation levels as high as 1200V. This association in a System In Package assembly allows optimal implementation of the autonomous power switch, regardless of the type of transistor (High Side / Low Side) and for switching frequencies up to 500kHz. Other features are also integrated, allowing appropriate management of the switch (3 state bipolar gate driving) and complete self supplied operation (efficient energy harvesting during the power device's Off and On states).

• *What's next?*

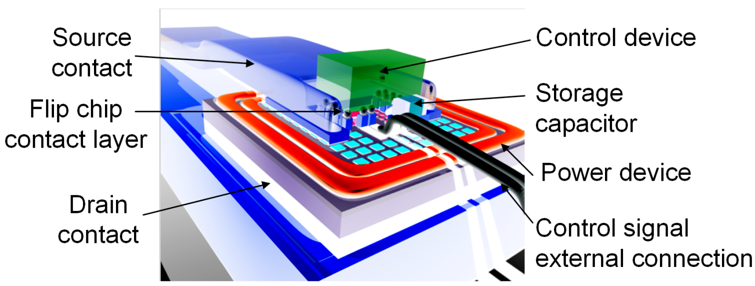
This integration effort is to be applied and transferred to the new platforms of power components (mostly SiC, GaN, and possibly diamond). The integration of the galvanic isolation stage can advantageously be formed by dielectric, wireless or optical coupling. These solutions are developed within our group. These new integrated features and power switches are also applied to new structures for the conversion of electrical energy.



Energy storage during power device switching transitions



Exemple of a dedicated CMOS driver including gate signal insulation, driver self supply and power gate charge control



Coupled design approach: dedicated CMOS driver above the vertical power switch

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FURTHER READING

L.T. Le, JC. Crebier, N. Rouger, «CMOS Integrated Optical Isolator for Power Transistor Gate Driver», IEEE IECON 2014, Dallas USA - Oct Nov 2014.

D. To, N. Rouger, J-D. Arnould, N.Corrao, Y. Lembeye, «Modeling and characterization of 0.35 µm CMOS coreless transformer for gate drivers», IEEE ISPSD 2014. Hawaii, USA, June 2014.

Low temperature cofired ceramics for integrated passive components

Thales society launched a project called MACOMAC HF (MAgnétique Cofrittés Multicouches pour l'Alimentation Compacte Haut Fréquence – Cofired multilayer magnetic components for compact high frequency power supplies) in which LGEP electrical engineering lab at Paris and G2Elab are attempted to achieve the development of a high frequency – high power density isolated converter dedicated to the study of LTCC technique (Low Temperature Cofired Ceramics).

The aim of the MACOMAC project was to evaluate cofired technology in order to realize multilayer magnetic components for the design of high frequency power supplies.

The current trend in power electronics to reduce the volume and increase the power density is higher switching frequencies. This raises the problem of the choice of components.

For active components, the use of GaN seems to be the way forward, even if the technology is not yet fully mature.

Passive components, especially magnetic components, represent the greatest problem of integration and thermal management. The solutions are based on high frequency ferrites (> 1 MHz) because metal alloys, crystalline, amorphous or nanocrystalline composites have too many losses.

However, conventional power ferrites from the diagram Mn-Zn have two disadvantages:

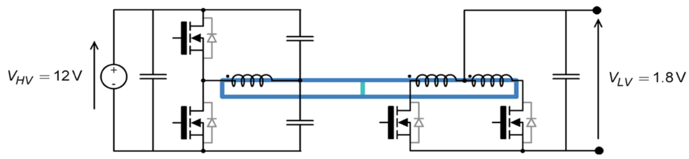
- High frequency losses are too high,
- The integration possibilities are limited as they are in the form of ceramics sintered at high temperature (> 1300°C), which requires the use of complex and bulky external coils.

A new family of ferrites has been developed in recent years by Thales: spinel ferrites NiZnCuCo. These ferrites have two important advantages:

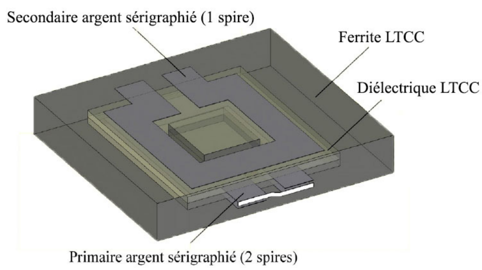
- They have very low losses at high frequency
- They can be sintered at low temperature around 900°C, below the sintering temperature of conventional ferrites, which allows them to be sintered with dielectrics and metals such as gold or silver.

The combination of these ferrites with dielectric low temperature sintering and silver metallization allows realizing magnetic components as inductors and transformers.

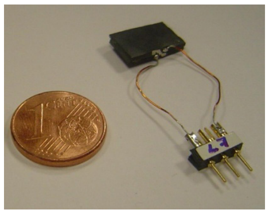
Inductor prototypes have tested on a buck converter when transformers are used on resonant converters.



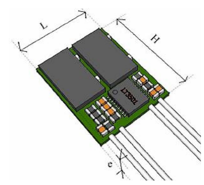
Resonant converter 12V/1.8V, 1W, 2MHz



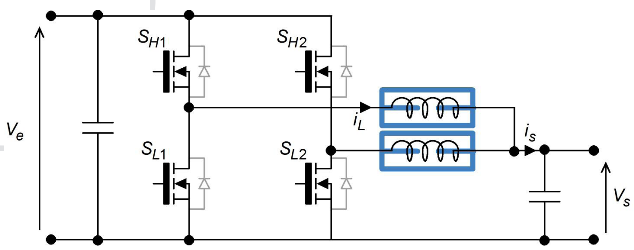
View of transformer
(primary: 1 turn, secondary: 2 turns)



Prototype of inductor
(400 nH)



Perspective: Point of Load 13 kW/litre



Interleaved Buck converter 12V/3.3V, 10W, 2MHz

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Characterization of power semiconductors and integrated circuits

Novel power semiconductor devices increase the stress on the measurements. For instance, larger current densities and high voltage capabilities are expected with wide bandgap material based devices such as eGaN Hemt, which can exhibit larger operating temperatures. The characterization benches developed in our group are well suited to accurately measure the static and dynamic performances of novel power semiconductor devices and their integrated function. Our equipments were mostly funded by Agence Nationale de la Recherche (ANR Topogan, ANR SiPowLight, ANR Eclipse) and are regularly updated and upgraded through new projects.

- ***Available equipments at G2Elab***

Three characterization benches are available in our group:

• DC measurements: On Wafer / Packaged devices, up to 3.3kV, up to 20 A (DC + pulsed). High voltage and High current probes. Agilent B1505 + HVSMU + HCSMU. Temperature controlled copper chuck, 25°C<T<250°C. See Fig 1.

• DC measurements: On Wafer / Packaged devices, up to 200V, up to 1 A (DC+pulsed), light illumination 200nm<Wavelength<1200nm. Keithley 2636A, 2401, Newport Monochromator and 150W Xenon lamp. Temperature controlled copper chuck, 20°C<T<100°C. See Fig 2.

• Switching performances: Packaged devices, up to 500V, up to 15A. Measurement bandwidth 50-150 MHz (up to 500 MHz – depends on dynamics).

A novel characterization bench is under development, featuring 83K<T<675K temperature range, less than 10-6 mbar vacuum, up to 10 kV voltage range (project Carapace, funded by Labex Lanef).

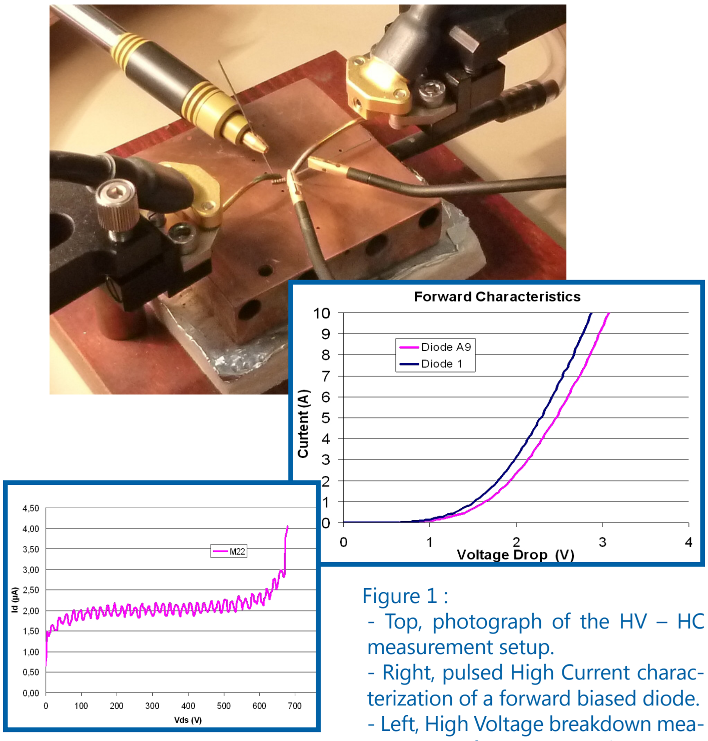


Figure 1 :
- Top, photograph of the HV – HC measurement setup.
- Right, pulsed High Current characterization of a forward biased diode.
- Left, High Voltage breakdown measurement of a power transistor

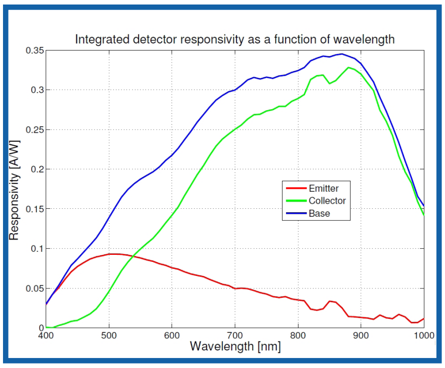
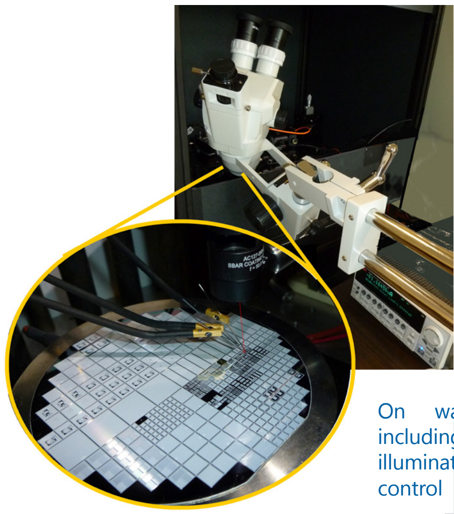


Figure 2 : Right, photograph of the electro optical measurement setup. Inlet, black box insuring ultra low noise. Left, measurement of the spectral responsivity of an integrated photo detector within a power device.



On wafer characterization, including variable optical illumination and temperature control

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a) R. Vafaei, JC. Crébier and N. Rouger, «Performance Measurements of an Optical Detector Designed for Monolithic Integration with a Power VDMOS», IEEE I2MTC 2013. May 2013 - Minneapolis MN.

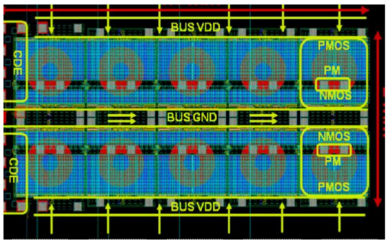
b) R. Grezaud, F. Ayel, N. Rouger, JC. Crebier, «A Specific Switching Characterization Method for Evaluation of Operating Point and Temperature Impacts on Wide Bandgap Devices», IEEE WipDa 2013. Oct 2013 - Columbus USA.

Micro-converters network:
A new approach for power converters design

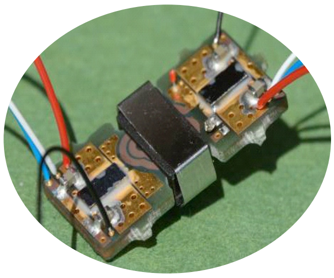
The high penetration of power electronics in the electrical energy management requires the development of flexible, generic, compact, reliable and low cost structure of converters. To achieve this goal, Micro-Converters Network permits a very efficient way of design using a generic cell.

Networks of micro-inverters offer a new approach to respond flexiblely to any specifications. This approach incorporates, in a sense, evolution produced in analog electronics with the advent of the operational amplifier. It aims to create a single component called Elementary Cell (EC), to meet all kinds of specifications, by networking a number more or less important of elements. The quantity to be addressed in any application of power electronics is energy, it is by association, in series and / or in parallel, of several of these elementary cells that the voltage and / or current of the converter caliber are achieve. The cell being generic, the development effort can be concentrated and the reliability and return management services greatly improved. This approach allows to substantially increase the penetration of power electronics but also new technologies into existing applications.

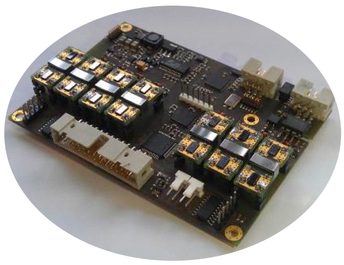
Therefore, an efficient and reliable structure, adaptable to many applications has been created. This Elementary Cell, highly integrated, used power dies achieved in CMOS technologie connected to a planar transformer to realise a Dual Active Bridge Converter to offer a very compact and fully reversible converter. Indeed, the ultimate need in terms of voltage and power is achieved by associating with each other, Elementary Cells, and then there is no need to adjust the structure to the power application. Thus the design of power converters in power electronics is simplified and becomes accessible to a wider range of applications.



Layout of the 5V 2A Elementary Cell power die.
Based on a standard technology this die offers a low cost and high efficiency active part to the Elementary Cell



10W-10kW/Liter Elementary Cell based on Dual Active Bridge structure using 2 power dies flip -chiped on a PCB including a planar transformer



Converter achieve by Elementary Cells connected on a mother board

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Modelling and design of electrical interconnection

For EMC analysis, the Electromagnetic modelling of interconnections is determining. Complex geometries, and various electromagnetic environment (magnetic or amagnetic metals, conductive carbon, ...), leads to require specifics methods. G2ELab works in this field since more than 20 years, developing an integral method named PEEC. Recently a compression matrix algorithm has been introduced, to increase the size and complexity of the modelled systems.

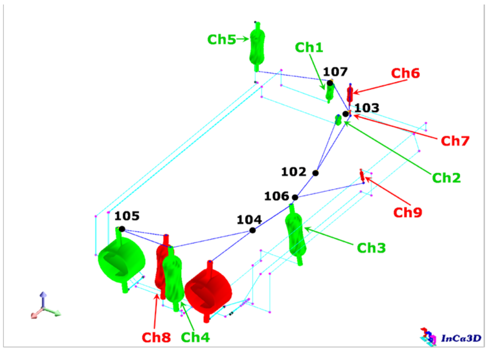
• *Modelling principe*

PEEC approach used is this work is an integral method using a zero-order Galerkin method, applied on parallelepipedic discretizing elements of the active parts only (only the conductine elements are meshed, not the air). This integration allows obtaining an equivalent electrical circuit using resistance, inductance and mutual inductance to represent the magnetic behaviour of the system. The complex matrix representation of this electrical circuit is full, therefore, the memory space used evolves in N^2 (N being the number of elements of the discretization). Furthermore, the complexity of a direct solver -typically based on LU decomposition- used to solve this kind of problem evolves in M^3 with M the degree of freedom. To decrease the complexity, we used an iterative solver FGMRes. To decrease the memory consumption, and accelerate the matrix – vector product, we used an Adaptative Multi Level Fast Multipol Method. With this approach it has been possible to model part of aircraft, including the metal structure, the carbon skin and all power routes. As an example, the impact of a lightning issue on the loads voltage has been studied, for various materials of aircraft skin (metal, various composite-carbon). These new developments will be implemented in the InCa3D software, and distributed by Cedrat company beginning 2014.

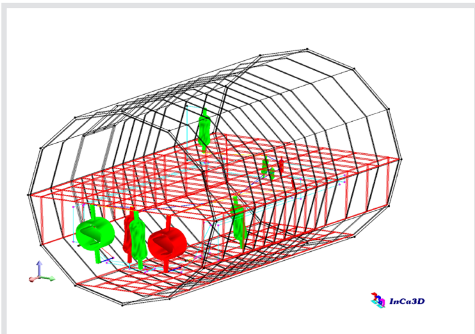
• *Design of a current path*

With the improved computation speed and a memory use, it should be interesting to explore optimal design. In our case, we used this modelling method to find an optimal layout for the current return path in a more composite aircraft. In this kind of problem the circuit topology is unknown at the first optimization step. The use of an electromagnetic modelisation tool (like InCa3D) is therefore not possible since the circuit linking all connecting points is not defined. To find a first solution we used a method based on the graph theory, and in a second step we used a classical optimization algorithm to improve this solution with respect to the electromagnetic behaviour (modeling using InCa3D), minimizing the conductor's weight.

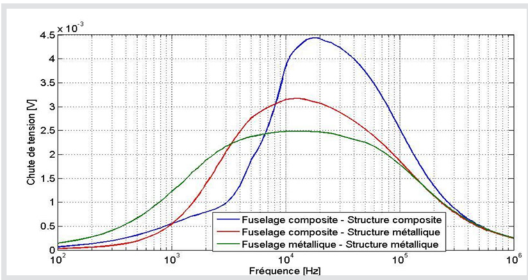
All these new developpements have been inplemented in the MIPSE (Modelling of Interconnected Power SystEms) framework, a new multi-levels and multi-methods computational electromagnetics environement.



Example of optimized current return path



Optimized current return path in its environment



Difference of Drop voltage for a load in frequency domain due to lightning with several materials for mechanical structure and aircraft fuselage.

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EMC and electromagnetic modeling of power electronics systems

EP

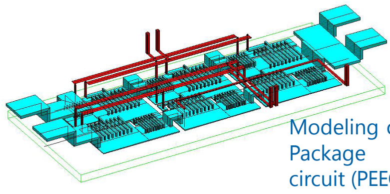
Power Electronics generates high frequency – high level disturbances, which have to be carefully managed, since they can prevent the system from working properly. The recent increase of devices performances (commutation speed) reinforces the need of powerful modelling and experimental characterization capability of electromagnetic phenomena associated with switching mode energy conversion.

I At component level: packaging issues

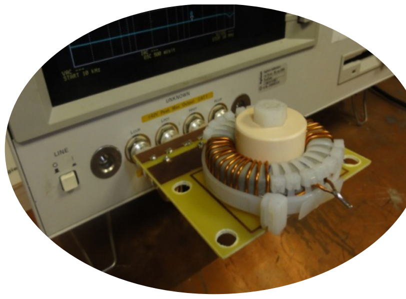
On an electromagnetic point of view, the design of a power semi-conductor package has to account for:

- The stray inductance, which is responsible for unacceptable voltage overshoots
- The reduction of common mode generation, issued by stray capacitances. To be noted that not all capacitances have negative effects, some of them have to be increased, or balanced each other
- The good design of the gate circuit layout, avoiding all disturbance from the power side

Precise impedance measurements, using various methods, greatly help in characterizing the different layouts and validating the simulations: Impedance measurement bridge, Network Analysers, Time domain Reflectometry, or other indirect experimental ways to extract stray impedance –oscillatory discharge, voltage overshoots, ...



Modeling of a Power Electronics Package including the gate circuit (PEEC Method in InCa3D ®)



Impedance Measurement Bridge, here used to characterize an inductor

II At converter level: filter design and best layout

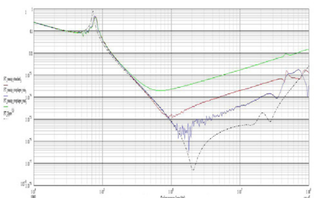
The filter size and cost usually represents 30% of the converter.

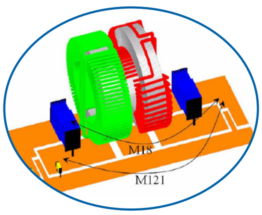
Optimization is thus needed to reach high performances with reduced size. Furthermore, stray couplings may reduce filter effectiveness and have to be taken into account.

- Filter elements can be optimized through dedicated EMC models of converters
- Filter layout as well as power components implantation may be obtained under EMC constraints. Optimization is possible thanks to suitable Electromagnetic Models

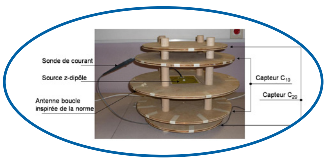
The magnetic close field can also be computed from the PEEC model of the converter; this is determining for the parasitic interactions between subsystems.

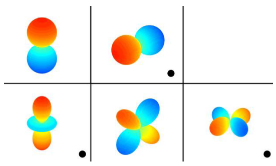
Experimental approach to characterize the EMC of a Power Electronics Converter involves conducted measurements using a Line Impedance Stabilization Network (LISN). Close field measurements are achieved using simple antennas, or dedicated sensors specifically developed to extract special information. Far field measurements are possible using anechoic chambers of our partners.





Modeling of an EMC filter including all stray couplings with components and PCB tracks. InCa 3D ® model. Different layouts comparison.



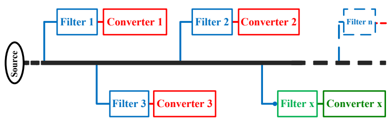


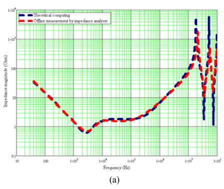
Specific magnetic field sensor, dedicated to dipolar and quadripolar component measurement (illustration of these components on the right)

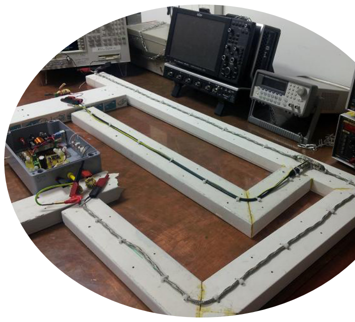
III At system level: a global approach

Usual EMC studies focus on one device in a standard environment. For instance, the LISN used for conducted emissions is not representative of the actual behaviour of the system. Furthermore, the EMC usual margins cannot lead to optimal system. There is thus a strong need of simulations representative from actual systems. To achieve this task, two solutions are simultaneously pursued:

- The ability to model large systems with PEEC method (such as an aircraft), using specific matrix compression methods, associated with order reduction methods
- The development of dedicated EMC models, using simple equivalent sources, adapted to system level studies.







Total input impedance of network containing two DC converters: comparison between theoretical model (blue colour) and measurement (red colour) in Differential Mode

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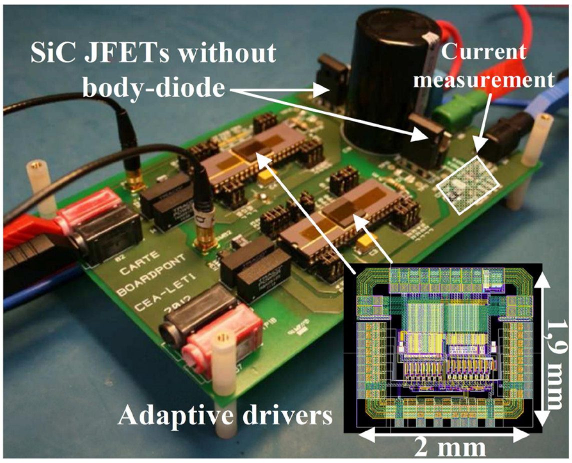
Collaborative strategic research with CEA-LETI

G2Elab and CEA-LETI have concluded a strong partnership to overcome today's limitations in power electronics. For instance, a joint research on several innovative projects is being addressed: packaging and modelling for power devices and power modules, integrated drivers design and characterization and radiated Electro Magnetic sources analysis in Electrical Vehicles. Both partners can benefit from their respective well known expertise, knowledge and platforms, already leading to recent breakthroughs widely recognized.

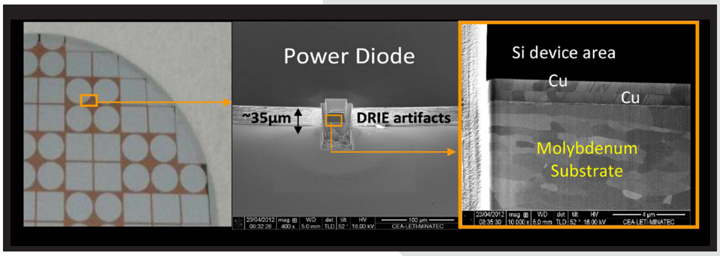
• *3D integration for power modules and integrated drivers*



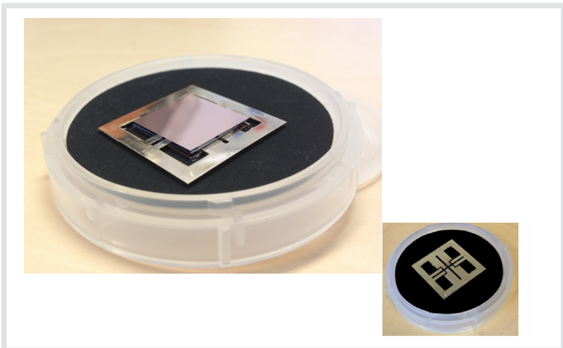
Dedicated driver for wide band gap power devices, including adaptive output stage

Specific integrated drivers are required when the highest efficiency is desired, both for 3D integrated switching cells and Wide Bandgap Devices (WBD). For example, an adaptive gate drive circuit has been successfully designed to provide a safer and more efficient control of WBD. The gate drive circuit fabricated in AMS0.35µm HV technology has adaptive output impedance for optimal turn ON turn OFF driving conditions and a gate side power transistor switching transition detection. Its impedance can be precisely adjusted during transition time according to the switched current to reduce overvoltage due to parasitic inductances. It can also be set to maintain the same transition times of WBD over a wide range of load currents, supply voltages and temperatures (25°C- 150°C). Therefore, in a synchronous buck converter based on WBD, the proposed gate drive circuit demonstrates secure but drastic dead-time reduction and therefore a significant gain in performances.

Direct bonding technology and trench isolation used for power device islanding are the cornerstone of this scheme of integration. Involving direct copper bonding layers, the technology is used during the mid-process to enable the wafer level bonding of vertical power devices to a joint metallic substrate while optimizing the devices intrinsic performances. Wafer level islanding and interconnect is used to simplify and guarantee the true 3D assembly at module level. This 3D assembly is based on the interconnect of matrices of low side and high side vertical power devices on top of each other. Our technology optimizes component surface height as well as alignments constraints. As a result, the true 3D integration of the active parts for power converters is optimized to the highest possible level, leading to strongly reduced EMI levels and increased switching speed capabilities.



Zoom into the bonding region between a vertical power diode and the metal substrate (Left: photograph, center and right: SEM).



Dummy 3D assembly of matrices of vertical power transistors and vertical power diodes. Inset: Zoom on the electrical interconnection frame

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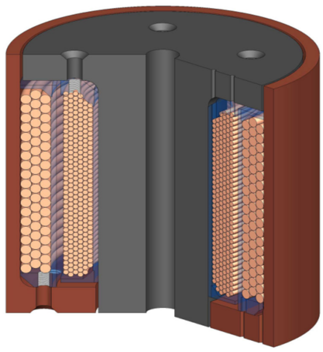
Further reading

a)N. Rouger, J. Widiez, L. Benaissa, B. Imbert, P. Gondcharton, B. Letowski, JC. Crebier, «3D Packaging for vertical power devices», CIPS 2014. Nurnberg, GERMANY, Feb 2014.

b)N. Rouger, L. Benaissa, J.Widiez, B.Imbert, V. Gaude, S. Verrun, JC. Crébier, «True 3D Packaging Solution for Stacked Vertical Power Devices».IEEE ISPSD 2013. May 2013 - Kanazawa JPN

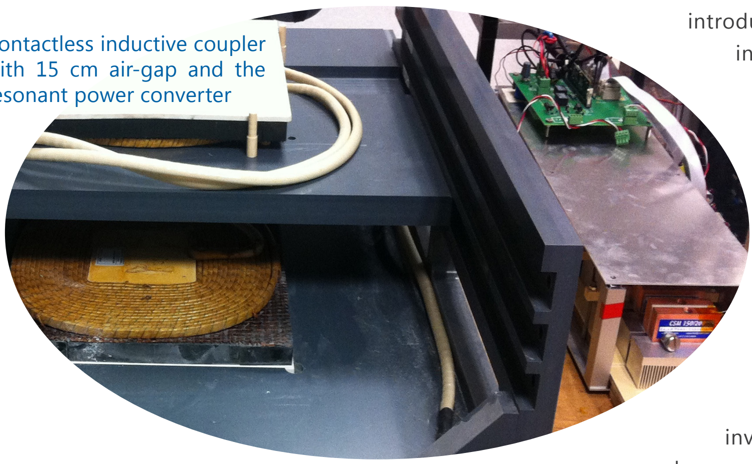
Resonant power converters for contactless energy transfer systems

Resonant power converters dedicated to contactless energy transfer have to fulfill some criteria as efficiency, cost, weight, volume, and finally electromagnetic compatibility. Although these systems are composed of two distinct elements, a converter and a resonant cell comprising a magnetic coupler and capacitors, these elements can't be separately designed. This research relates to various applications such as aeronautic applications and battery chargers for electric vehicles or submarine robots.



Rotating contactless inductive transformer

Contactless energy transfer systems involve large air gap transformers with magnetic core. To design the whole system, it is necessary to consider the influence of inductive parameters on electrical magnitudes and the converter which supplies this magnetic device. Indeed, this kind of magnetic device has a large leakage inductance and a small magnetizing inductance. Therefore, to transfer the desired power, the transformer needs important reactive power to magnetize the magnetic core and to provide leakage flux. Like inductive parameters can be determined only when geometry is known, sizing has to be iterative. Moreover, resonant converters can be used to compensate inductive behavior, but modify electrical constraints of the transformer.

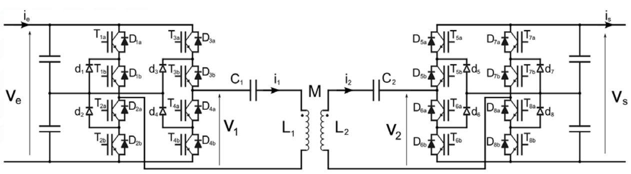


Contactless inductive coupler with 15 cm air-gap and the resonant power converter

Because of low magnetic coupling factor ($k < 0.5$), it is necessary to introduce resonant capacitors in order to compensate high inductive behavior. The compensation mode depends on the kind of converter used and the coupling quality. For DC-DC voltage conversion, a capacitor in series with the primary can compensate the voltage drop across leakage inductance with Series-Parallel compensation and the primary inductance with Series-Series compensation. The secondary capacitor can be either in series or in parallel. When it is connected in series or in parallel, secondary capacitor compensates respectively magnetizing inductance and secondary inductance.

This principle allows soft switching to be introduced for both inverter and rectifier, which can significantly reduce switching losses without generating higher conduction losses.

These soft switching principles have been applied to the DC/AC power supply dedicated to transfer power to a rotating part through a coaxial magnetic coupler. The objective is to supply a piezoelectric actuator for a vibratory mechanical drilling (Avibus project).



DC/DC series-series resonant converter for Electric Vehicle battery charger (20kW)

A high power DC-DC converter has been implemented dedicated to charge the batteries of electric vehicles. A three levels NPC inverter and rectifier are associated with a magnetic coupler whose coupling factor is less than 0.3.

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