February 2021

LES RENDEZ-VOUS FIABILITE DU CFF

EPowerDrive Project

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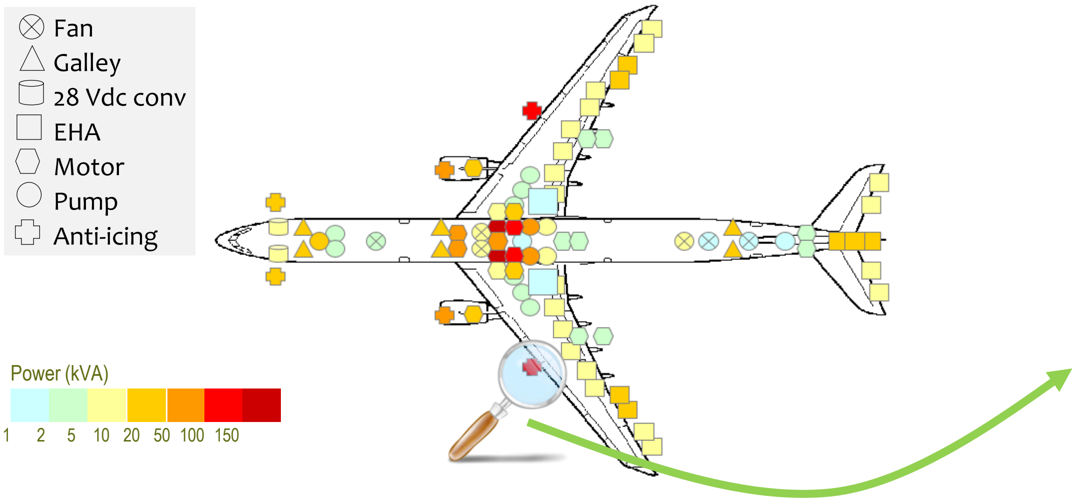
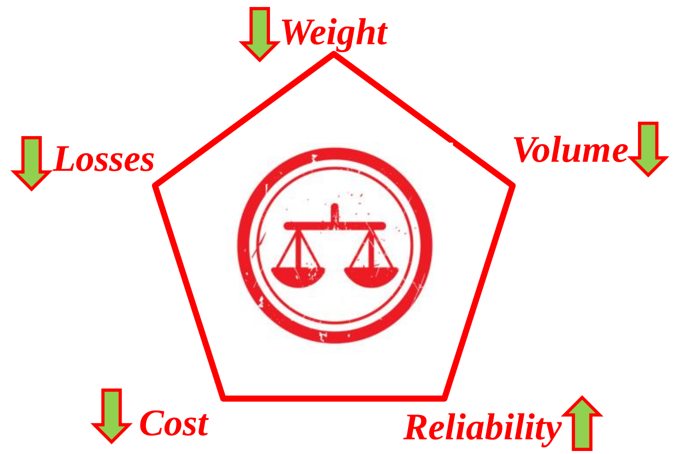
Senior Expert on Power Electronics

Electrical Applications in Aircrafts

More Electrical Aircraft

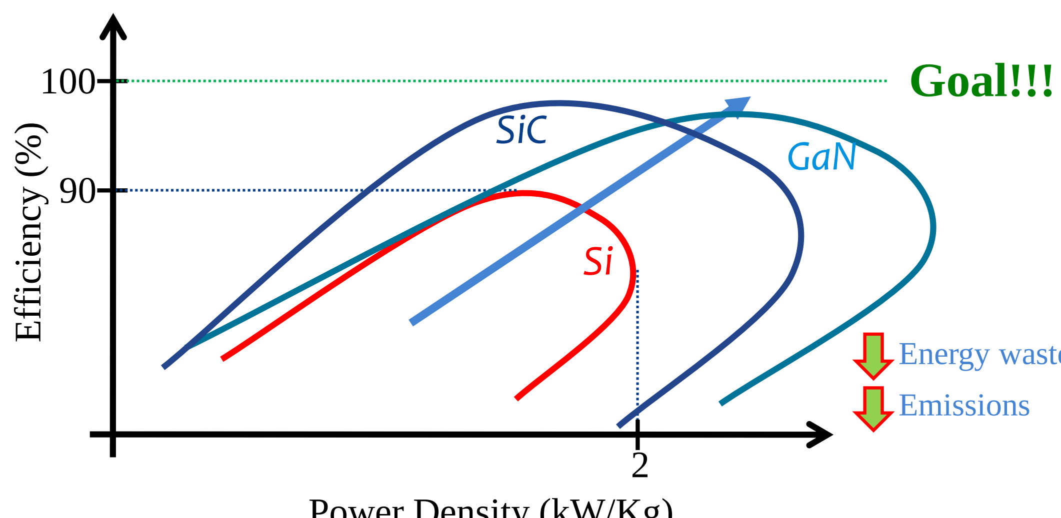


Trade-off in power converters:



Wideband Gap Semiconductors

SiC **GaN**



E-POWERDRIVE

OBJECTIVES

- Propose technologies, models and tools to increase power density and efficiency of the the whole electromechanical chain using WBG semi-conductors (Silicium Carbide SiC and Gallium Nitride GaN)

8,4 M€

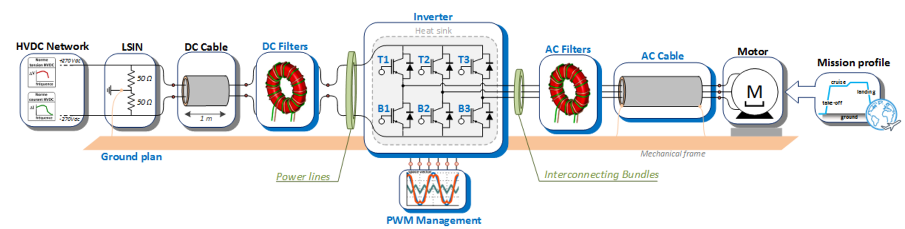
48 months (oct.17 – oct 21)

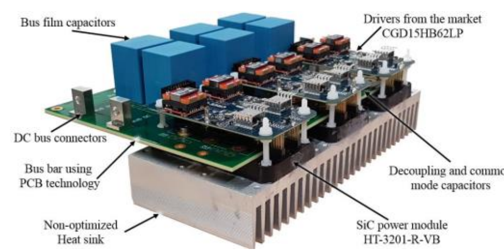
AEROCONSEIL, AIRBUS, APSI 3D, ELVIA PCB, LIEBHERR, NIDEC/LEROY SOMER, SAFRAN, (TFE ELECTRONICS), ZODIAC, LAPLACE, SATIE, G2ELAB

Key Results

- **WP1 (Optimisation)** → Tools for Multi-Disciplinary Optimisation
- **WP2 (EMC)** → HF models for optimized filter design
- **WP3 (Power Electronics)** → Technologies for high-power density, high efficiency inverter
- **WP4 (Electric Motors)** → Models for better understanding of iron losses, potential of additive manufacturing

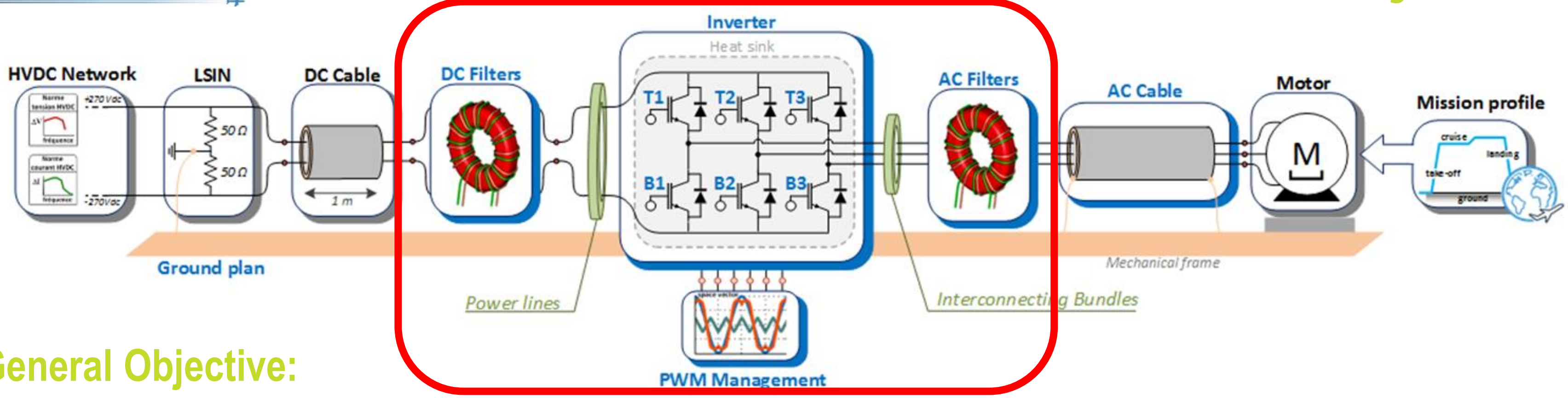
2 Demonstrators (1 based on SiC, 1 based on GaN)





6 patents | 3 PhDs | 15 publication | 10 partners | 22 people

EPOWERDRIVE - Objectives



General Objective:

- ❑ Contribute with models, characterization results and technologies in order to help optimizing the Power Drive System

Specific Objective:

- ❑ Design, Built and Test a Full Compliant 70kVA/56kW/540V THREE-PHASE INVERTER

SiC-Based

Power Core
Efficiency = 99%
P. Dens. = 15kW/kg

Reference Filter
Efficiency = 99.2%
P. Dens. = 5.3kW/kg

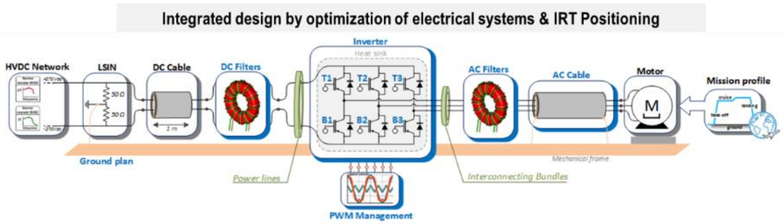
- Simple Topology, reliable and performing components, optimized efficiency and filters

GaN multilevel

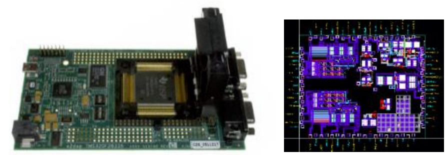
Power Core + Filters
Efficiency = 98.5%
P. Dens. = 8kW/kg

- Performing Topology, components and technology for maximum integration

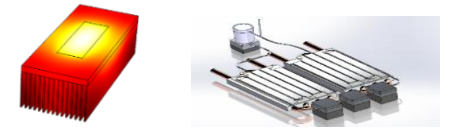
Research Topics on EPowerDrive



Multidisciplinary design optimization of electrical system

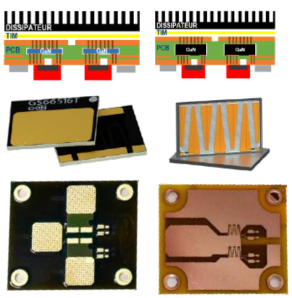


Control card & algorithm, optimized PWM, active gate driver



Cooling system optimization

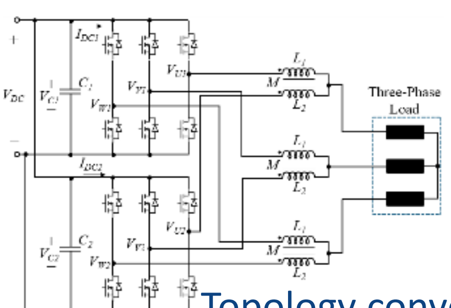
Component, power module & magnetics loss characterization



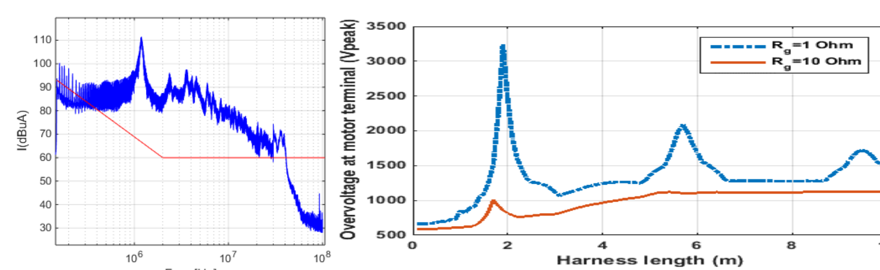
GaN PCB embedded

Innovative SiC power module

High efficiency & integrated SiC & GaN Power Converter

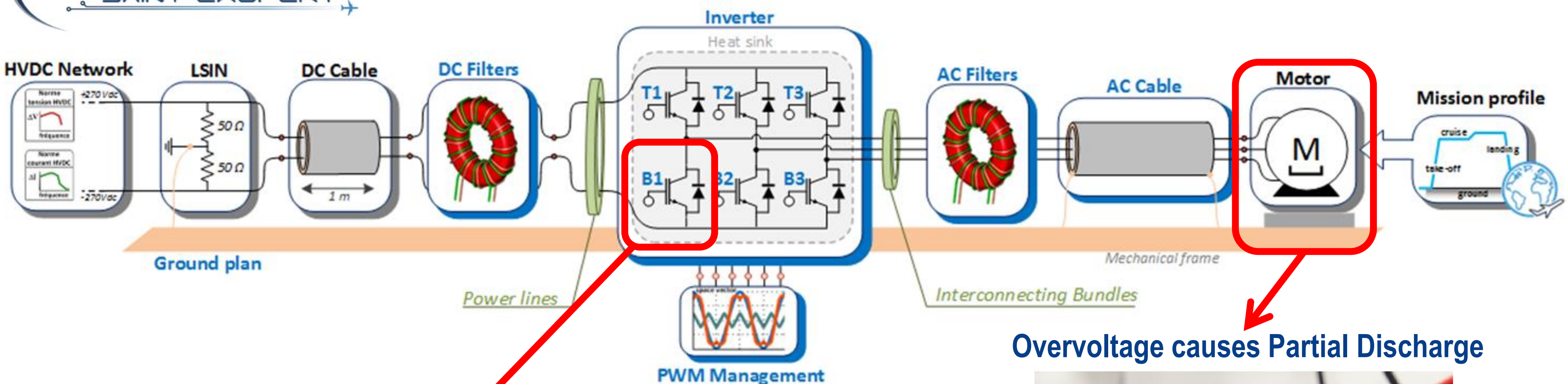


Topology converter

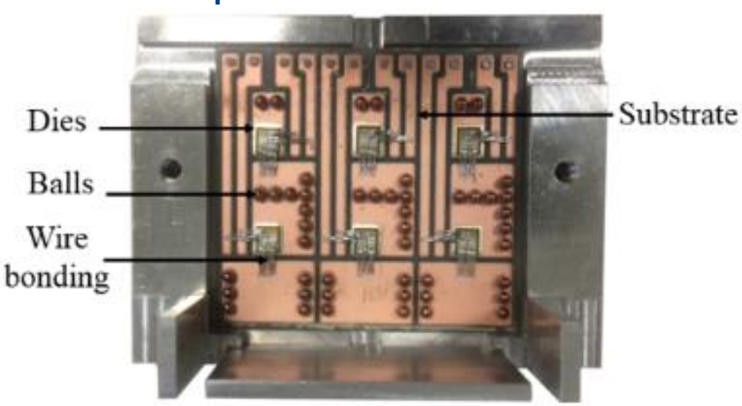


EMI, overvoltage & partial discharge impact evaluation

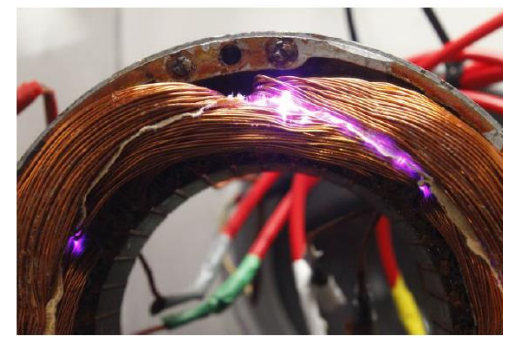
EPOWERDRIVE – Reliability



Overvoltage and temperature causes power module failure



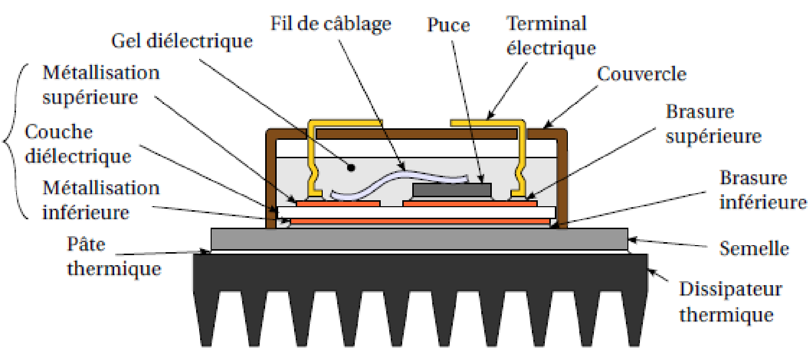
Overvoltage causes Partial Discharge



Partial Discharge causes motor failure

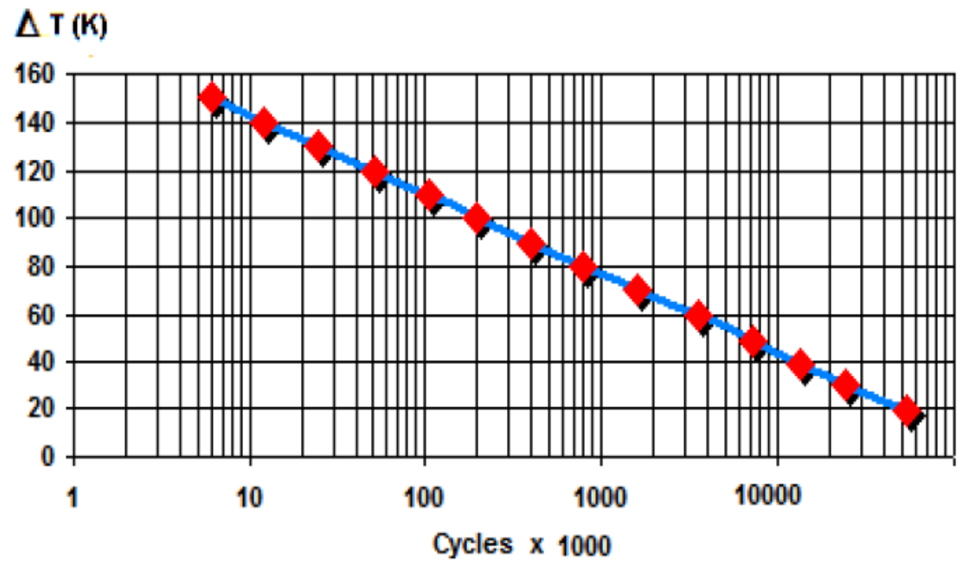
Reliability of SiC Modules

Power Module



Internal structure of a generic power module [1]

Reliability of a power module



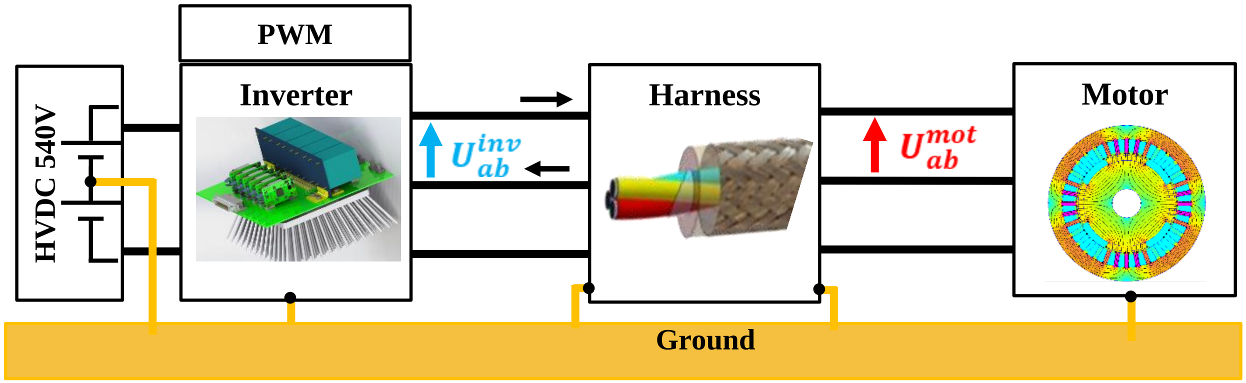
Number of cycles to failure versus temperature variation of MOSFET dies inside a power module for automotive applications [2]

- Small SiC dies = thermal impedance smaller than that of Si.
- Thermal cycles at fondamental frequency can be significant.
- Fast SiC switching induce higher overvoltage at drain-source and gate-source terminals, which may reduce component lifetime.

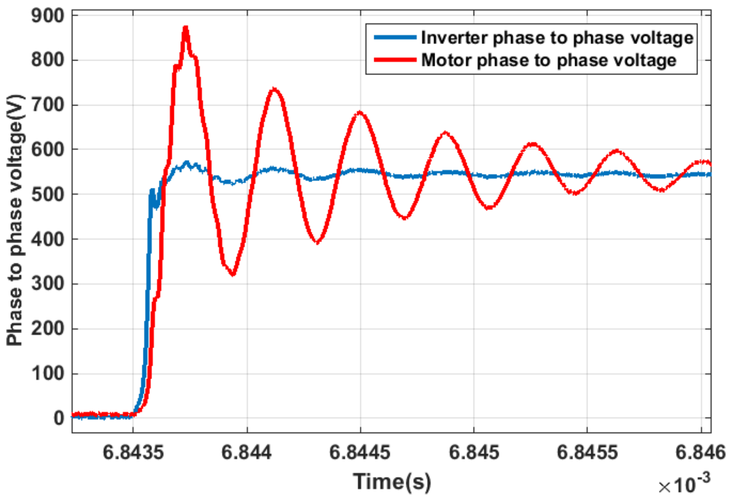
[1] B. Mouawad, "Assemblages innovants en électronique de puissance utilisant la technique de « spark plasma sintering »," Ph.D. dissertation, Institut National des Sciences Appliquées de Lyon, 2013
[2] A. Testa, S. De Caro, S. Panarello, S. Patane, "Stress Analysis and Lifetime Estimation on Power MOSFETs for Automotive ABS Systems" IEEE PESC 2008

Partial Discharge and Overvoltage

- **Phase to phase** overvoltage in electromechanical chain : inverter + harness + motor



- Example of measured overvoltage on **AC motor + 2m harness fed by IGBT inverter (IRT platform)**



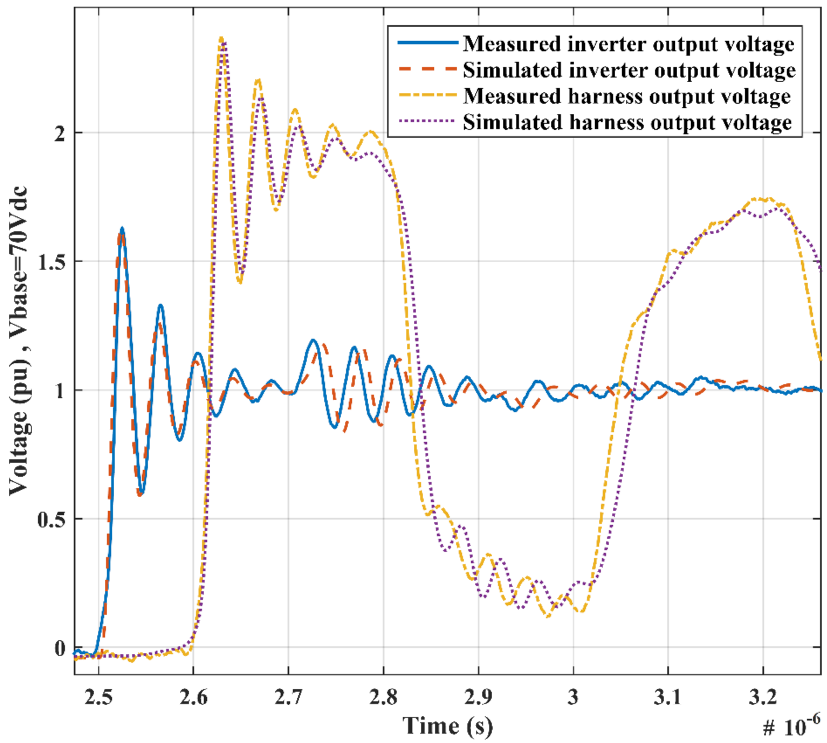
→ **Propagation and reflection phenomena along the harness, even for small lengths, cause voltage overshoots across the motor phases**

Impact of SiC on PD

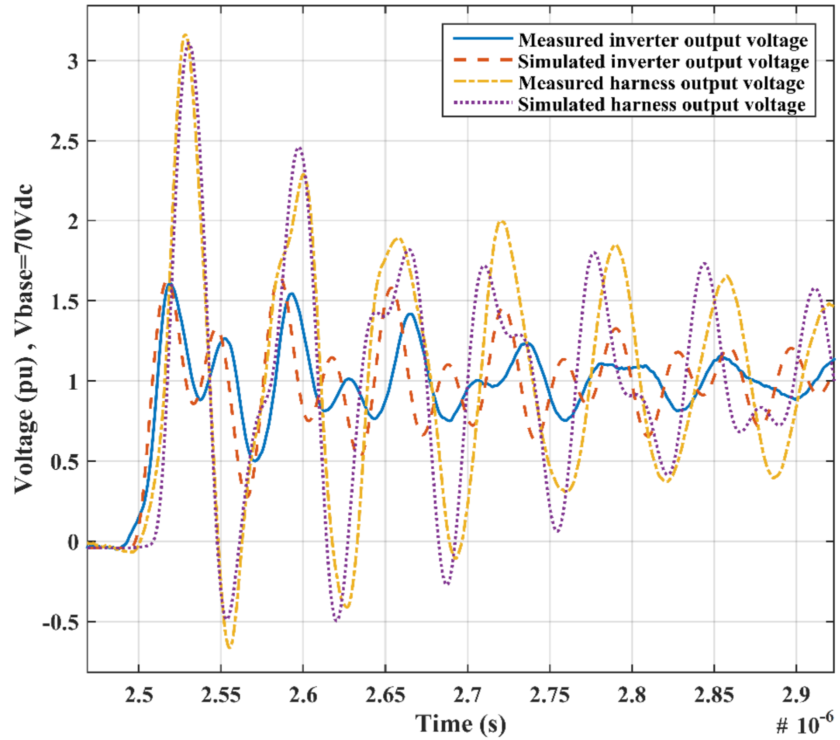
Experimental Investigation

Overvoltage caused by SiC inverter fed a short CF-AWG18 harness having…

Length of 18.7 m

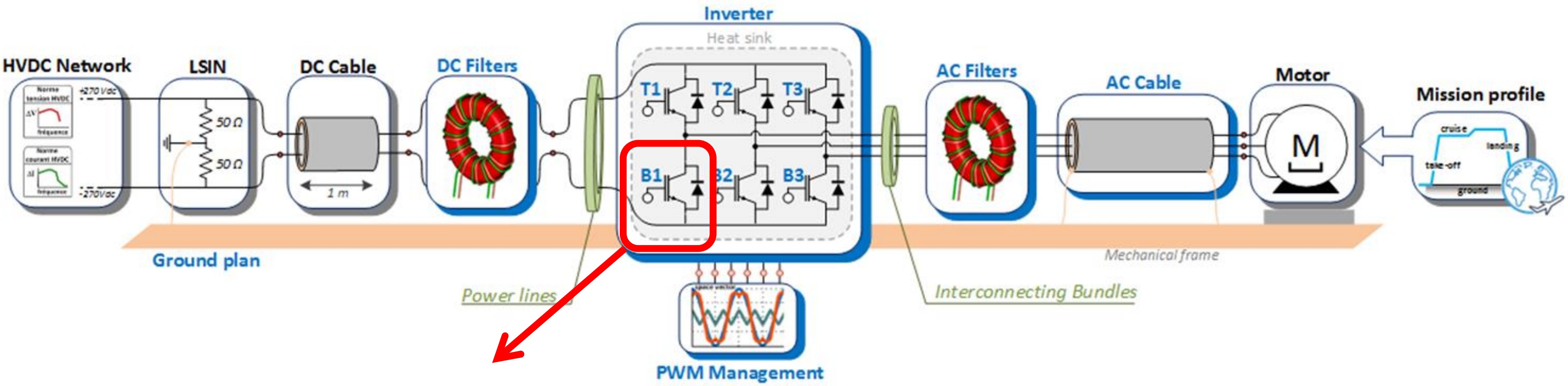


Length of 2.3 m



- Very high overvoltage can appear on cables end if its length has a characteristic frequency close to the ringing frequency at the output of the converter
- Simulation with our developed frequency models is fast (**Calculation time < 200ms**) and matches very well experimentation (**Accuracy < 6%**)

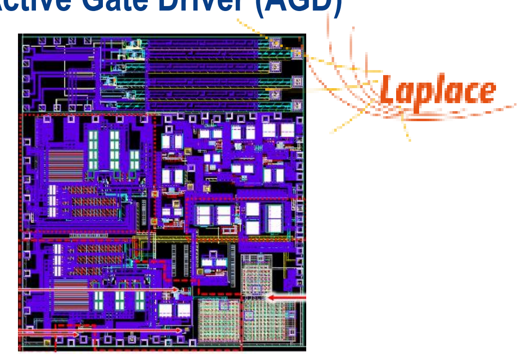
EPOWERDRIVE – Reliability



Improving reliability of Power Drive System

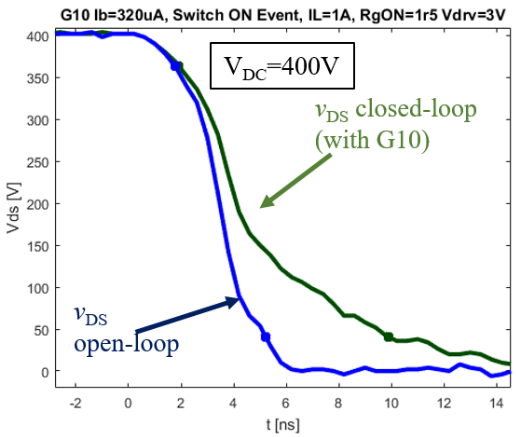
- Reduce Overvoltage
- Reduce Switching Speed
- Reduce Maximum Temperature
- Reduce Thermal Cycles

Active Gate Driver (AGD)



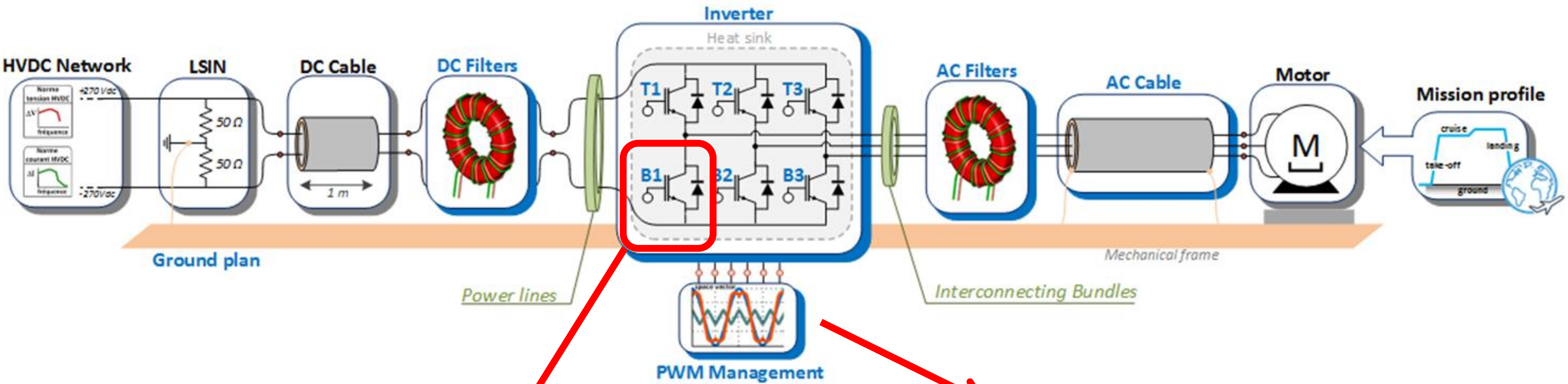
Implementation of AGD

Experimental Results



Developed AGD reduce switching speed, overvoltage with small increase on switching losses

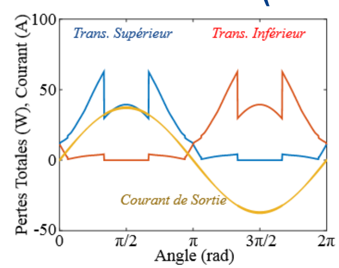
EPOWERDRIVE – Reliability



Improving reliability of Power Drive System

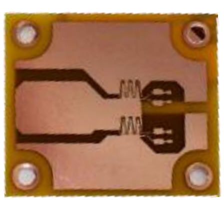
- Reduce Overvoltage
- Reduce Switching Speed
- Reduce Maximum Temperature
- Reduce Thermal Cycles

Control Methods (PWM)



Optimal PWM method to reduce losses and thermal cycles

Packaging and Integration

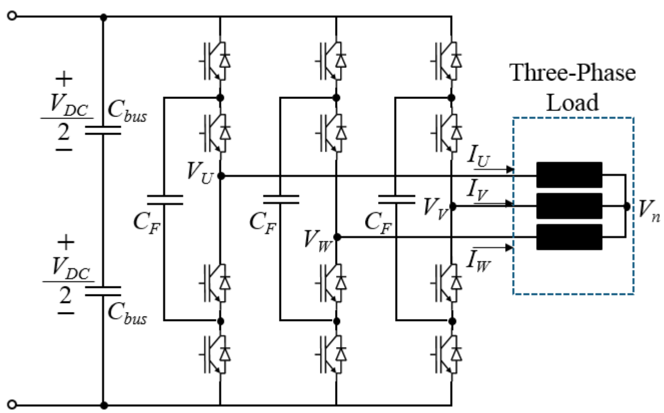


GaN inside PCB

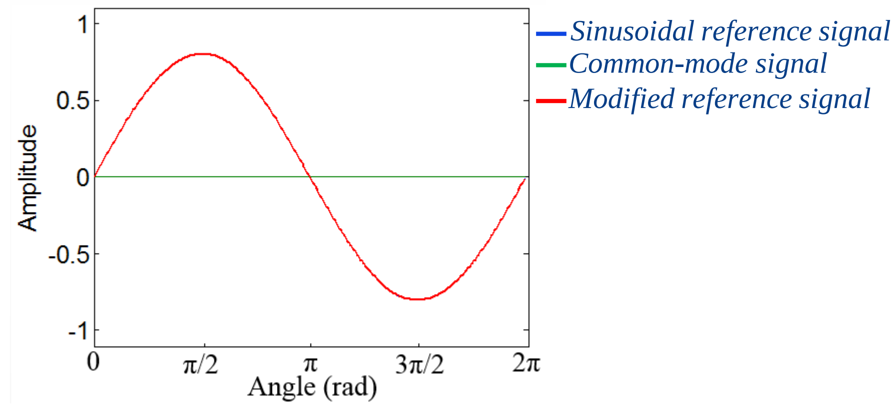
Innovative SiC power module

PWM Methods (Common mode offset)

Floating Neutral Point Configuration

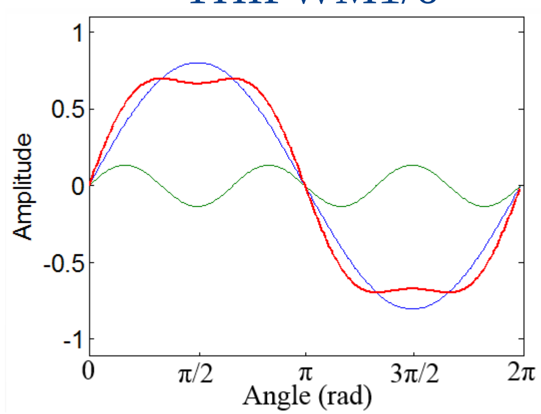


SPWM



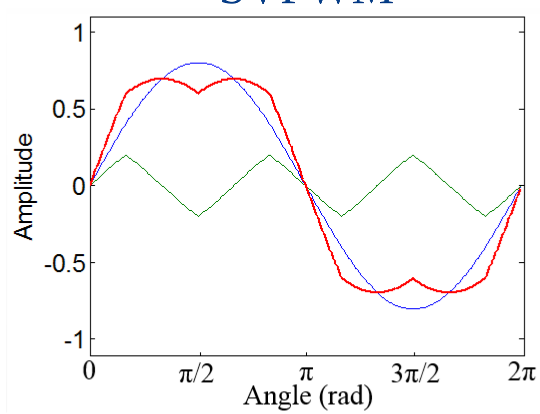
Continuous PWM Methods

THIPWM1/6



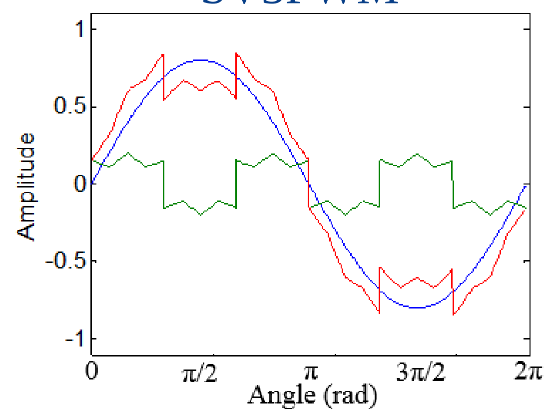
Increase output voltage range

SVPWM



Reduce output voltage harmonics

SV3PWM

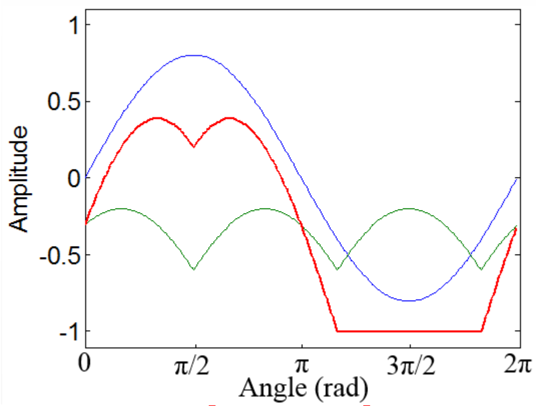


Reduce output voltage harmonics for 3-level conv.

PWM Methods (Common mode offset)

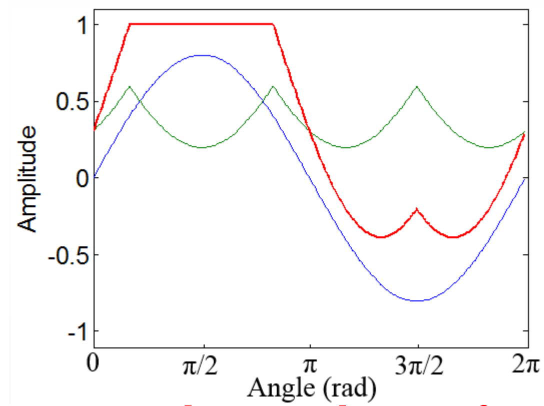
Discrete PWM Methods

DPWMMIN



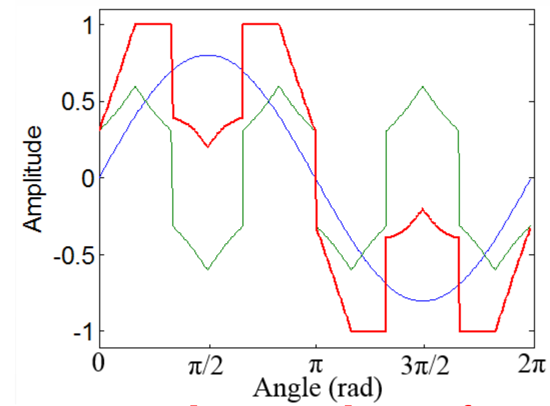
Reduce SW losses of low-side switches

DPWMMAX



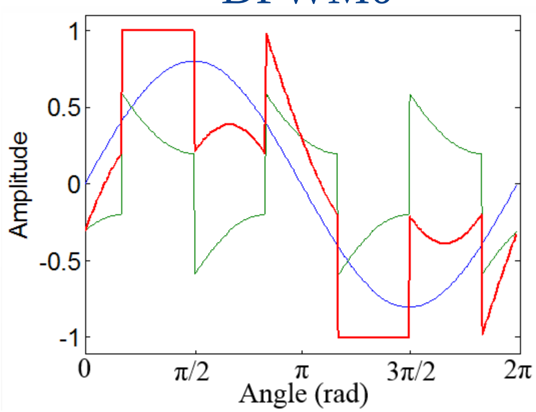
Reduce SW losses of high-side switches

DPWM3



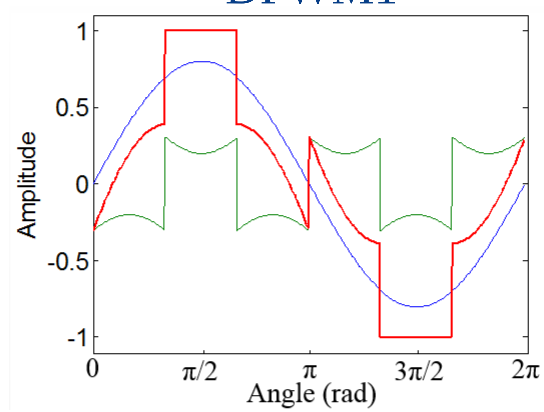
Reduce SW losses for non-sinus current

DPWM0



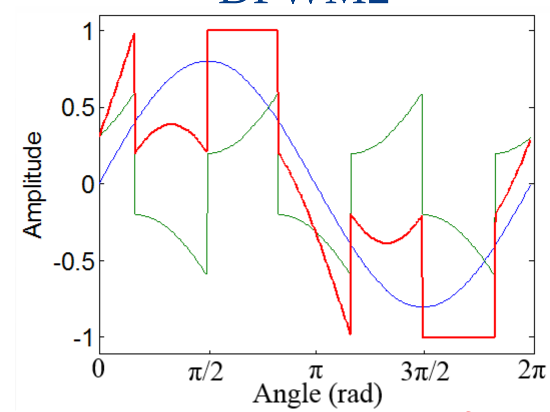
Reduce SW losses for capacitive load

DPWM1



Reduce SW losses for resistive load

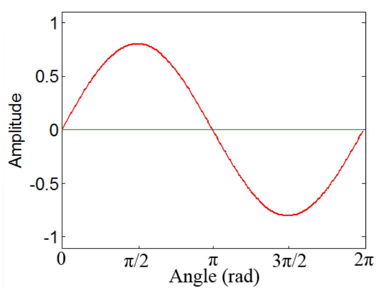
DPWM2



Reduce SW losses for inductive load

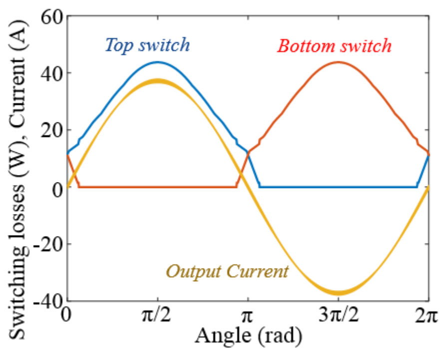
Influence on Losses (2-Level Converter)

SPWM

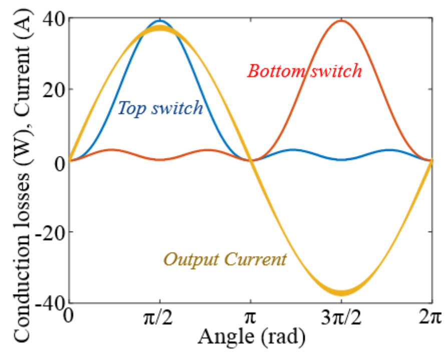


Losses = 152W

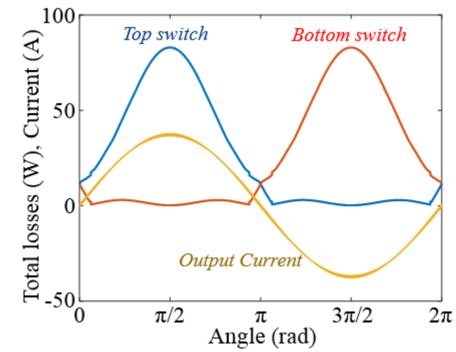
Avg Switching Losses



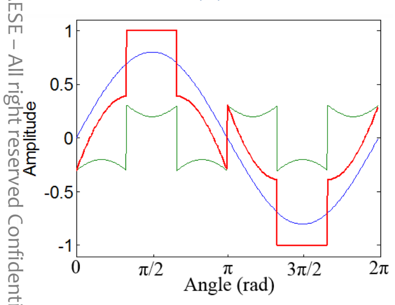
Avg Conduction Losses



Total Transistor Losses

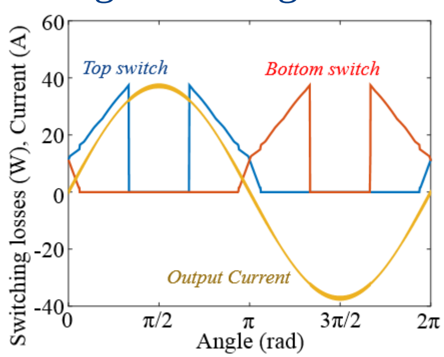


DPWM1

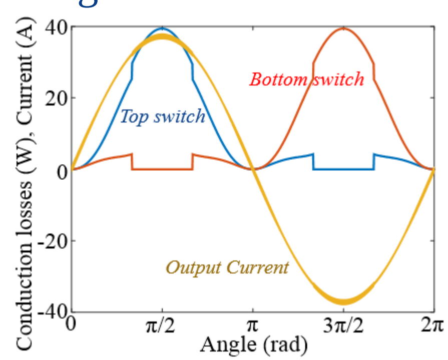


Losses = 110W

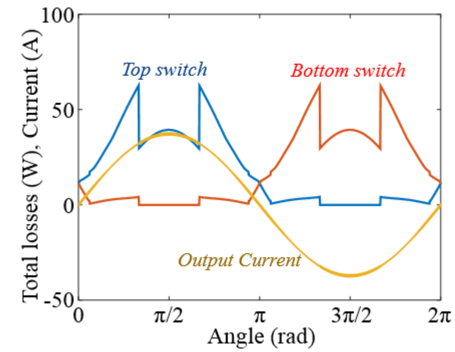
Avg Switching Losses



Avg Conduction Losses



Total Transistor Losses

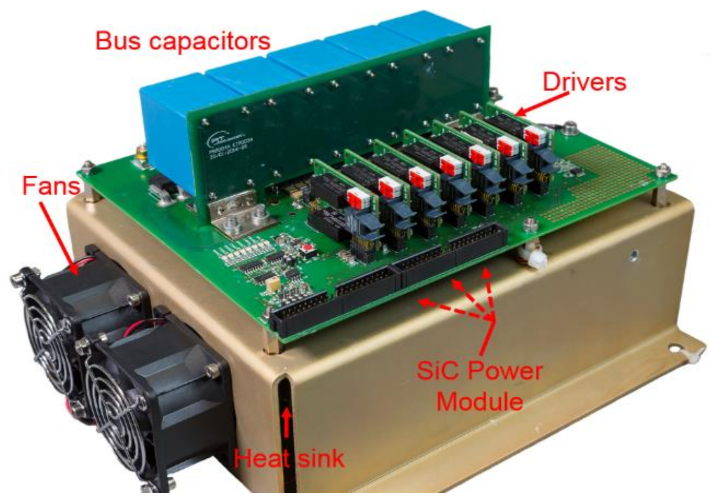


Total losses decrease 28% at 50kHz using a more "adequate" PWM method

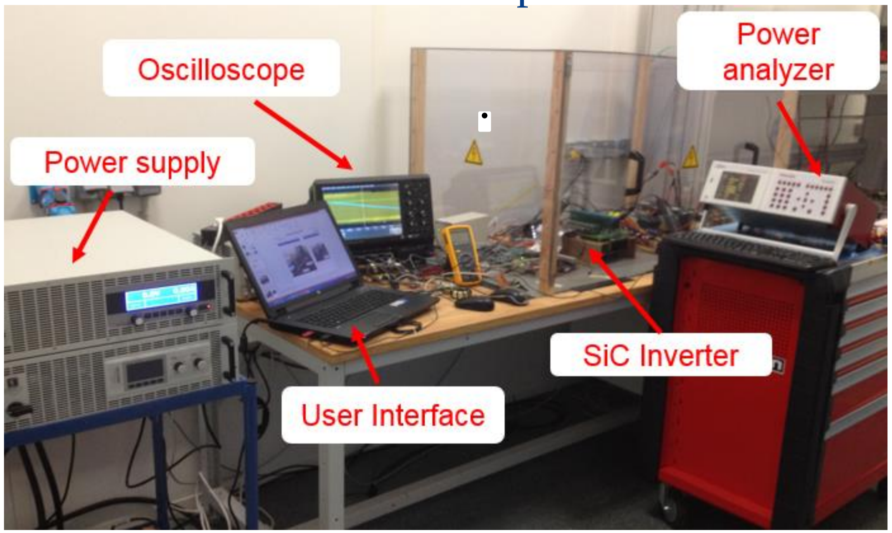
PWM Methods (Experimental Results)

Three-phase SiC Inverter (15kW/540V)

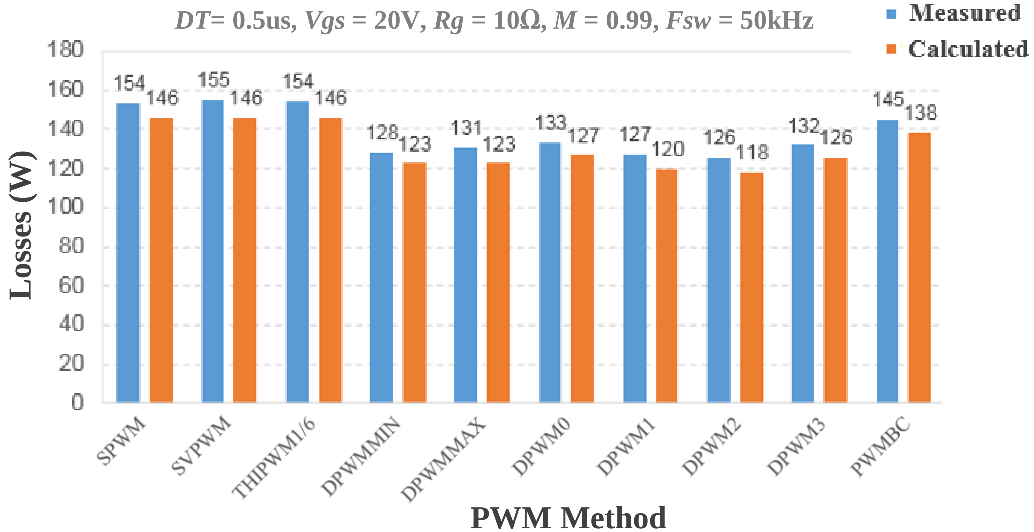
Three-Phase Prototype



Test Setup



Losses for different PWM methods

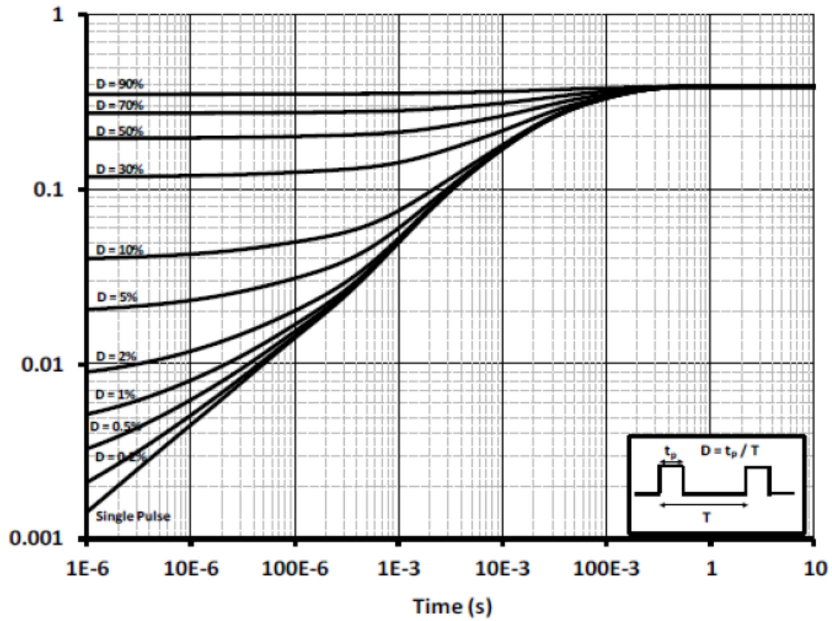


- *Pout* ≈ 14kVA, efficiency can attain **99%** with the DPWM1, at *Fsw* = 50kHz.
- Maximum of 5% difference between measured losses and estimated losses using characterization method, for any PWM method.

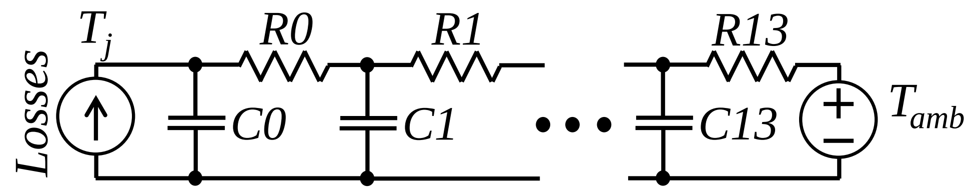
Thermal Impedance

Thermal impedance characteristics

6-pack 1200V/50A
SiC MOSFET



Thermal impedance model



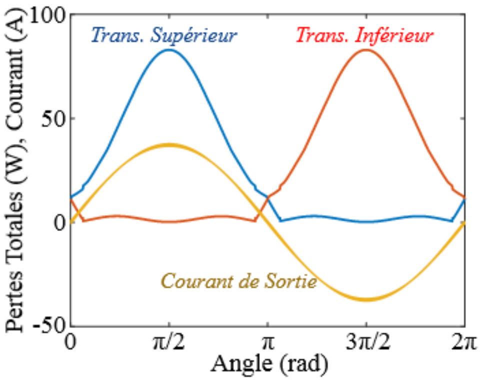
Résistance thermique (K/W)	
R0	$4{,}18\times10^{-3}$
R1	$7{,}49\times10^{-3}$
R2	$7{,}33\times10^{-2}$
R3	$1{,}41\times10^{-2}$
R4	$5{,}83\times10^{-2}$
R5	$4{,}24\times10^{-2}$
R6	$2{,}80\times10^{-2}$
R7	$2{,}30\times10^{-2}$
R8	$2{,}40\times10^{-2}$
R9	$2{,}42\times10^{-2}$
R10	$2{,}33\times10^{-2}$
R11	$2{,}21\times10^{-2}$
R12	$1{,}86\times10^{-2}$
R13	$6{,}80\times10^{-3}$

Capacité thermique (J/K)	
C0	$3{,}07\times10^{-3}$
C1	$7{,}93\times10^{-3}$
C2	$1{,}89\times10^{-2}$
C3	$9{,}41\times10^{-3}$
C4	$4{,}42\times10^{-2}$
C5	$5{,}33\times10^{-2}$
C6	$8{,}55\times10^{-2}$
C7	$1{,}87\times10^{-1}$
C8	$3{,}64\times10^{-1}$
C9	$6{,}51\times10^{-1}$
C10	1,22
C11	2,47
C12	5,01
C13	25,1

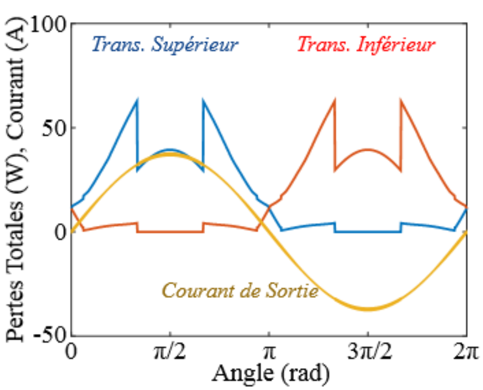
Thermal Cycles

Instantaneous Losses

SPWM



DPWM1



Thermal impedance of SiC Power Module

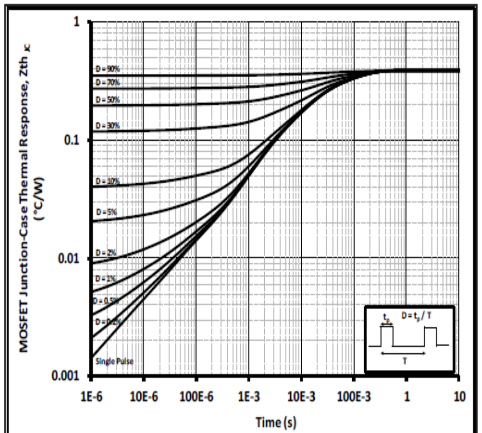
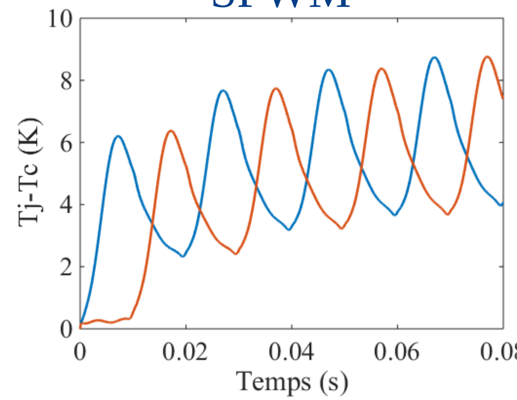


Figure 29. MOSFET Junction to Case Thermal Impedance

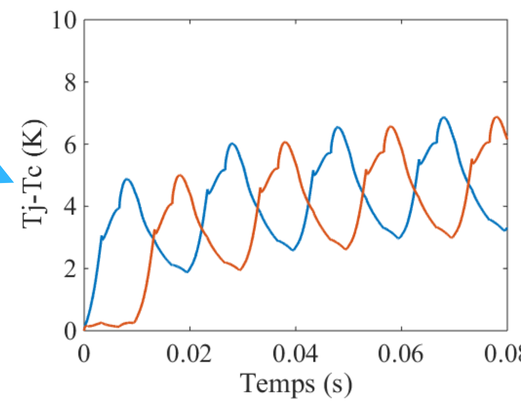
Instantaneous temperature difference between junction and case

SPWM



ΔT= 4.9°C

DPWM1



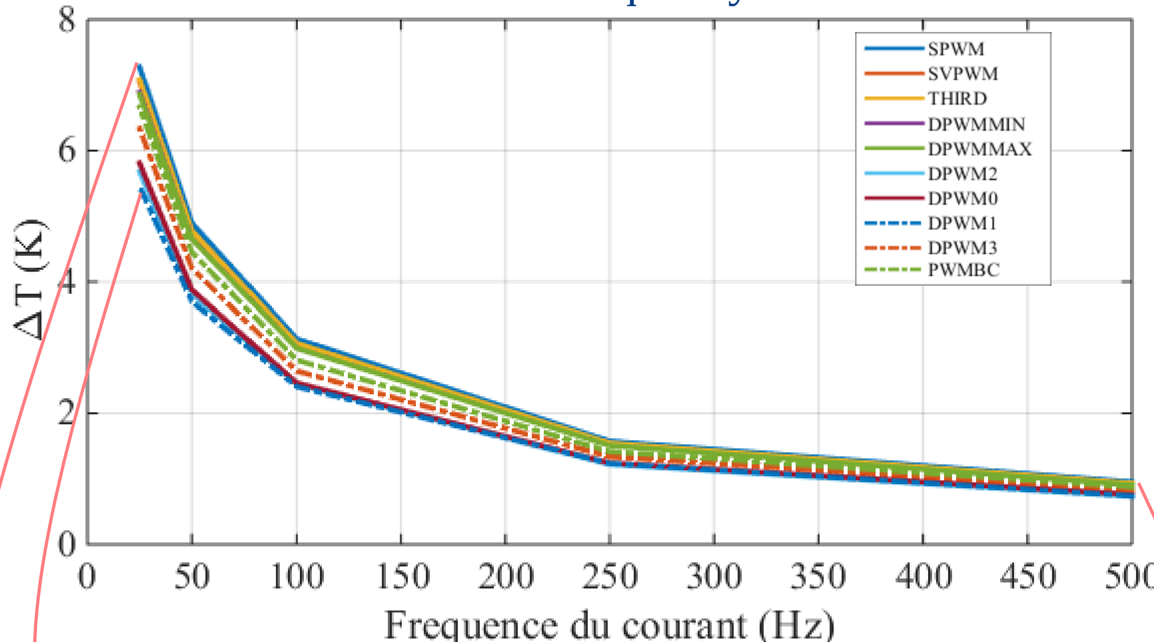
ΔT= 3.7°C

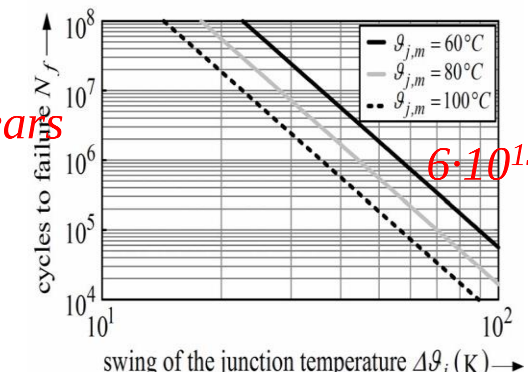
Thermal cycle amplitude of junction temperature

Operating Point

Parameters	Values
Power	15kVA
DC voltage	540V
Output current	26.3A
Mod Index	1.0
Sw Freq	50kHz
Fund Freq	50Hz
Cosϕ	1
PWM method	Sinus
Vgs	-4V/+20V
Rg	1Ω
Deadtime	500ns
SiC MOSFET (1200V/50A)	CCS050M 12CM2

Fundamental frequency variation





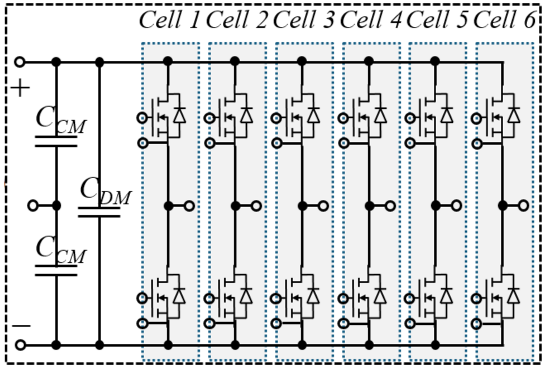
5,4K at 25Hz
$10 \cdot 10^9$cycles=12.7years

7,2K à 25Hz
$3 \cdot 10^9$cycles=3.8years

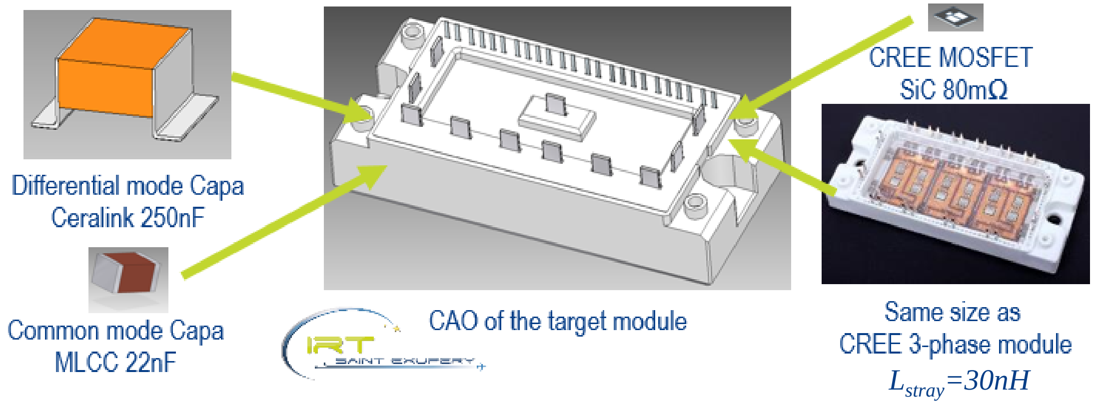
1K at 500Hz
$6 \cdot 10^{13}$cycles=3800years

CULPA: SiC Module

Topology and Components

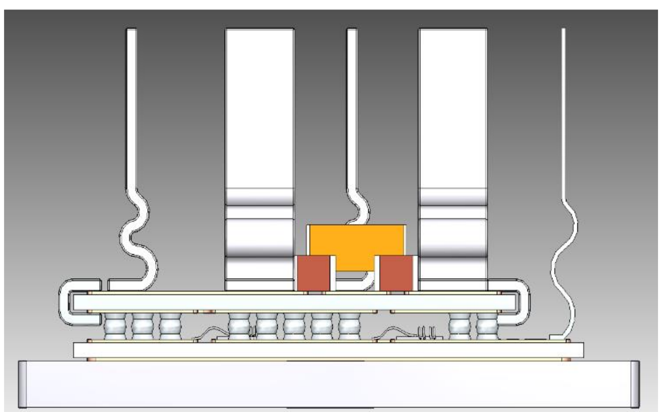


Internal Circuit of Power Module



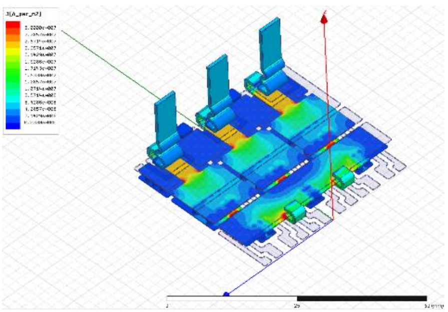
Main components

Architecture and Different Versions

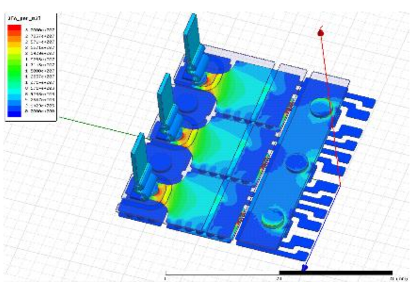


2 DBCs to decrease surface and to reduce capacitor temperatures

Design of 2 Versions



Version: Ring (L_{stray}=20nH)

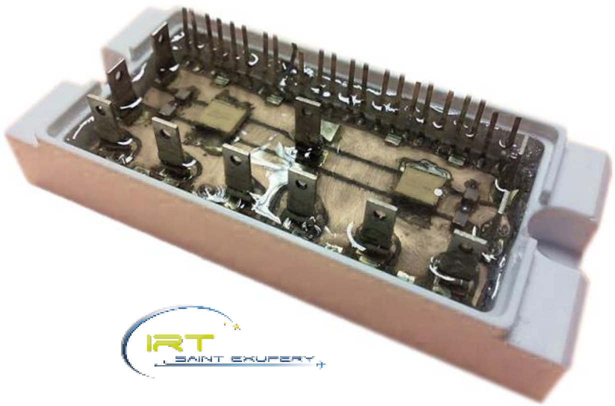


Version: Vias (L_{stray}=16nH)

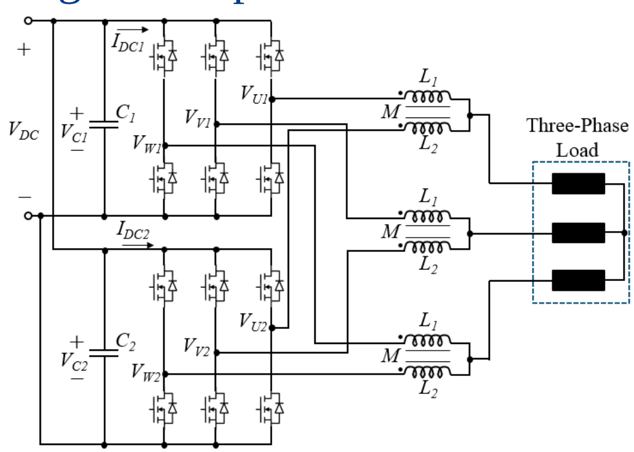
Version "Vias" made with performing DBC (Si3N4) to reduce parasitic inductance et resistance

CULPA: SiC Module

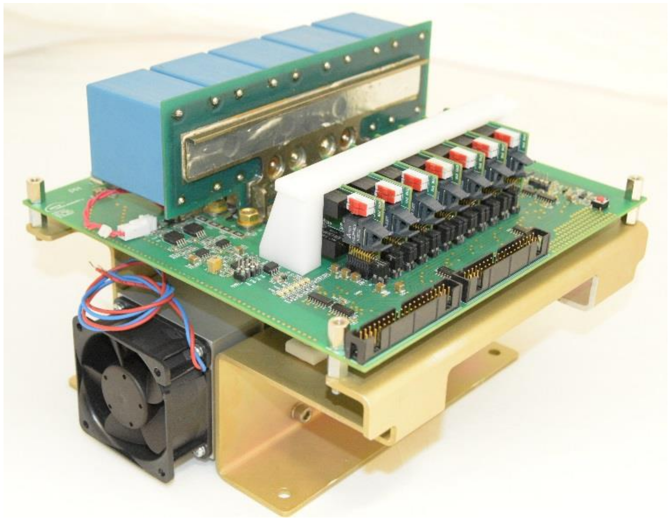
Designed SiC Power Module



Circuit of Multilevel Converter Using Developed SiC Power Module



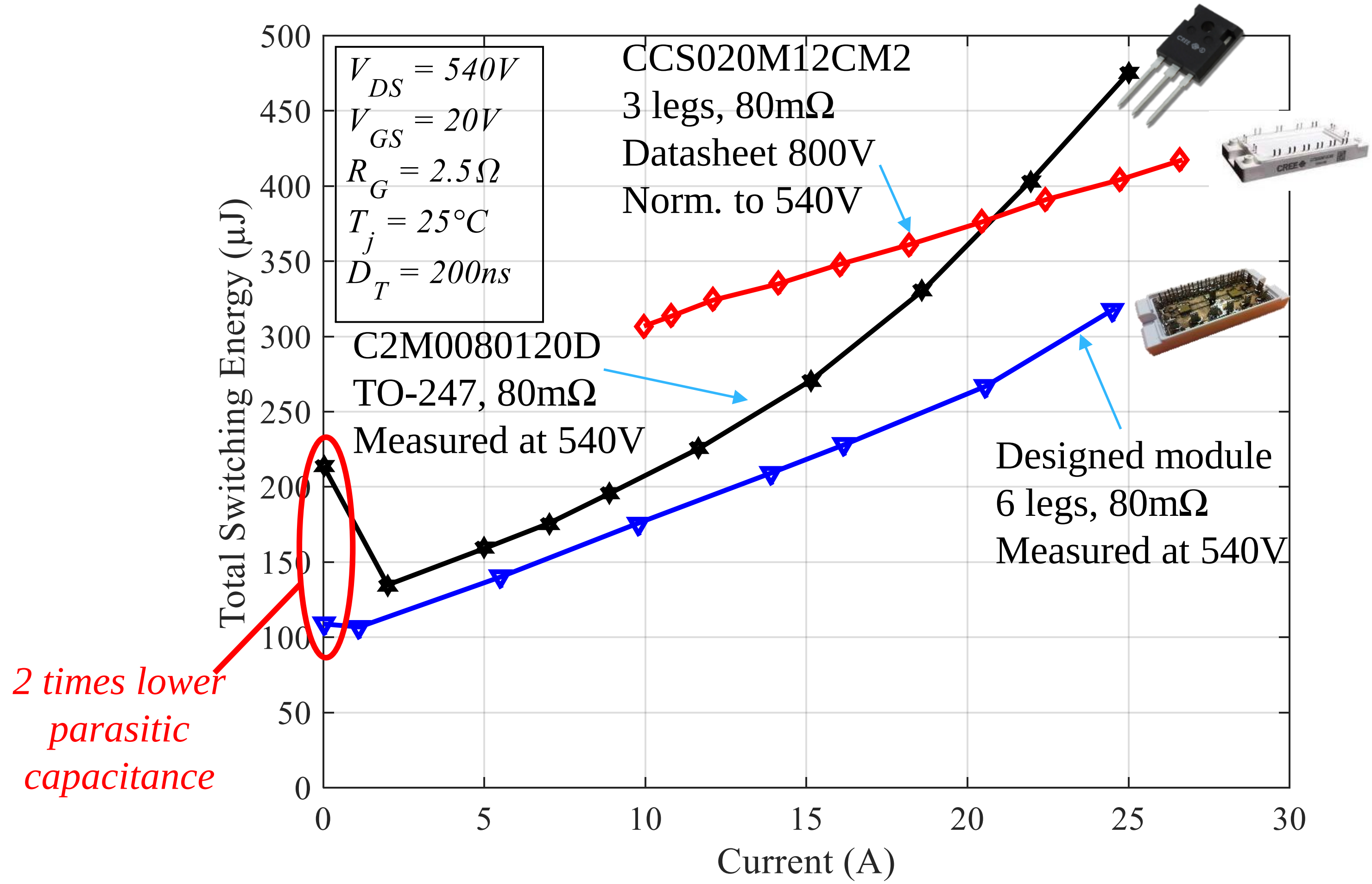
Parallel Multilevel Inverter (540V/15kVA)



- Characterization of SiC module using the Modified Opposition Method
- Evaluation of losses, EMI and overvoltages in a double three-phase (parallel multilevel) converter using coupled inductors

Experimental Results

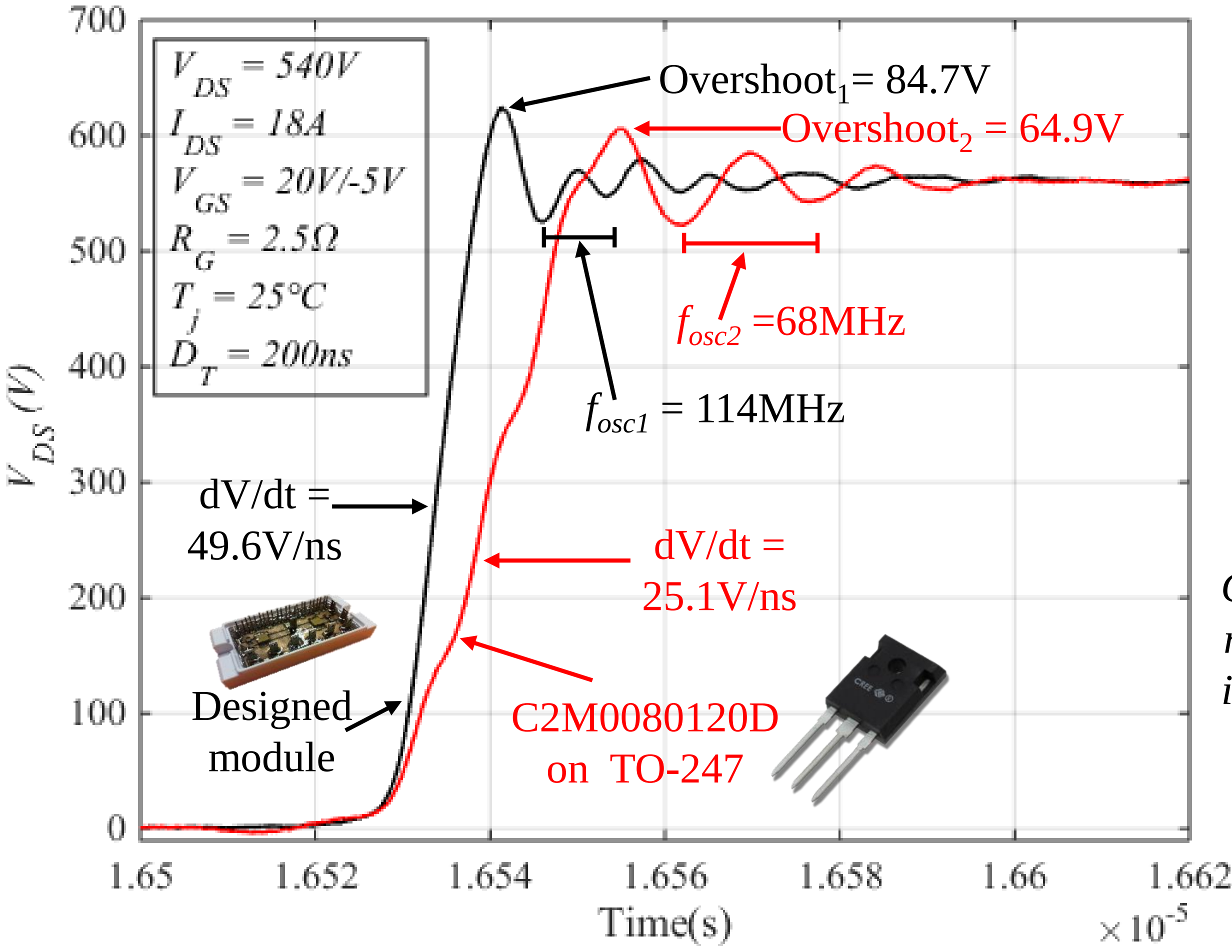
Comparison between different components and modules



- Designed power module presents lower losses than commercial power module and discrete component with the same die

Experimental Results

Comparison between different modules



f_{osc2}/f_{osc1} = 2.8

If
$C_2=2\cdot C_1$

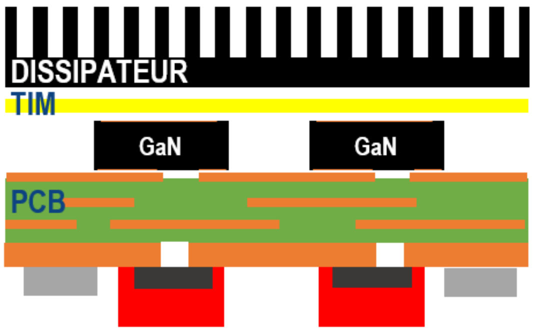
Then
$L_{stray2}/L_{stray1}=1.4$

Close to theoretical ratio between stray inductances of both solutions 28nH/20nH

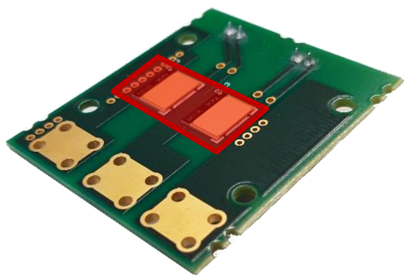
- Designed power module presents higher speed and low overshoot when compared to discrete component using the same die

GaN Inside PCB

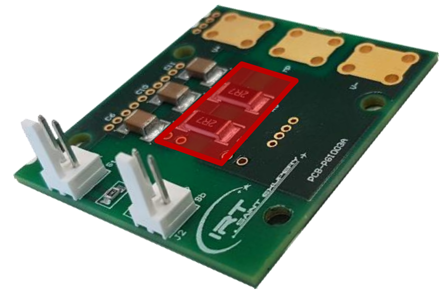
Standard



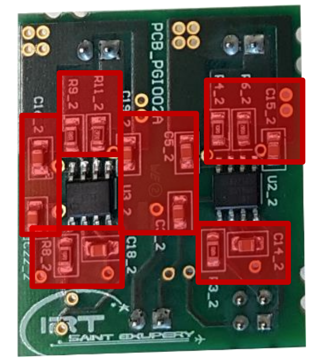
Top Surface



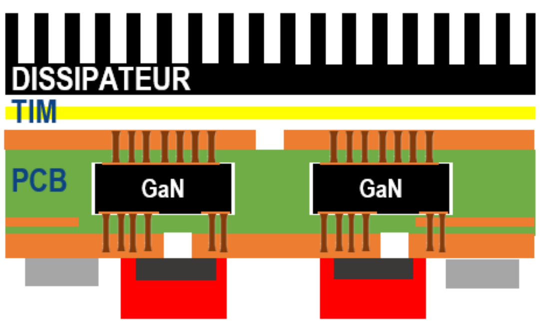
Bottom Surface



Driver



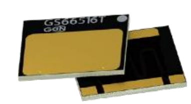
Embedded



Goals:

- **Increase power density**
- **Improve thermal and electrical performance**

Packaged Component



GS66516T
60A, 25mΩ
Top cooling

Bare Die

GS-065-060-2-D
60A, 25mΩ

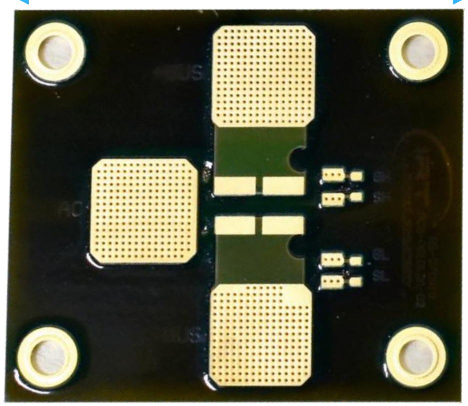
GaN Inside PCB

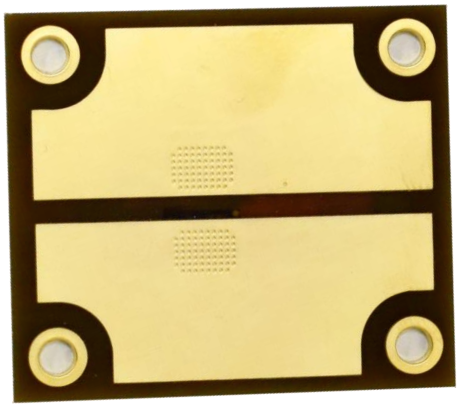
GS66516T
60A, 25mΩ
Top cooling

Embedded GaN pre-packaged die

52mm

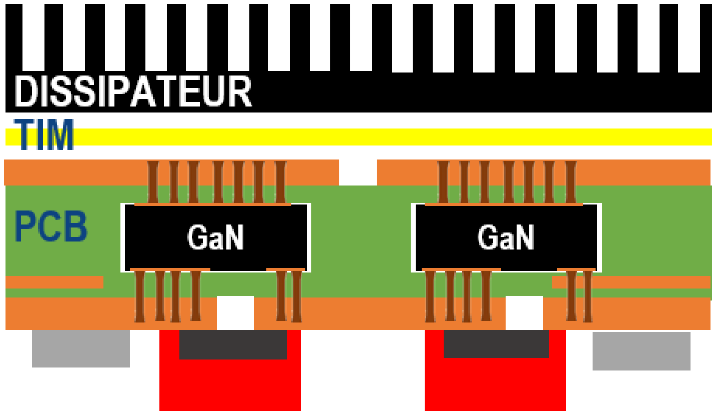
45mm





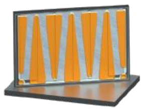
Thermal pad surface 731mm²

Copper thickness 250µm



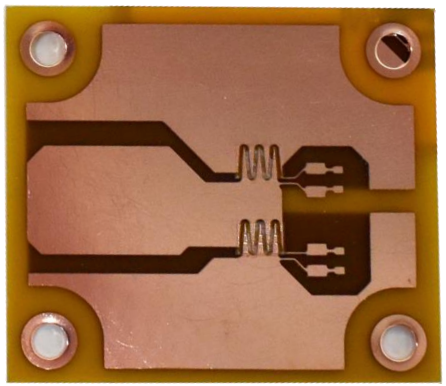
- Good thermal resistance
- Very low inductance

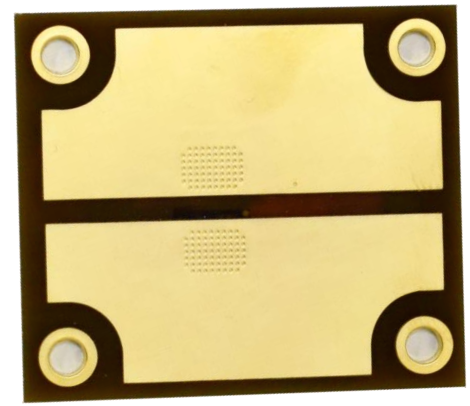
GaN Inside PCB



GS-065-060-2-D
60A, 25mΩ

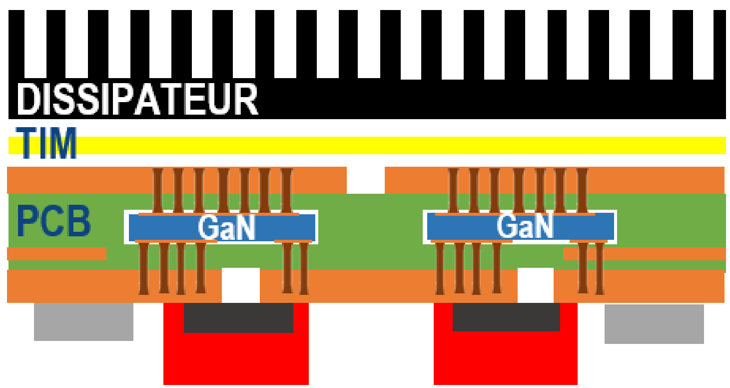
Embedded GaN bare die





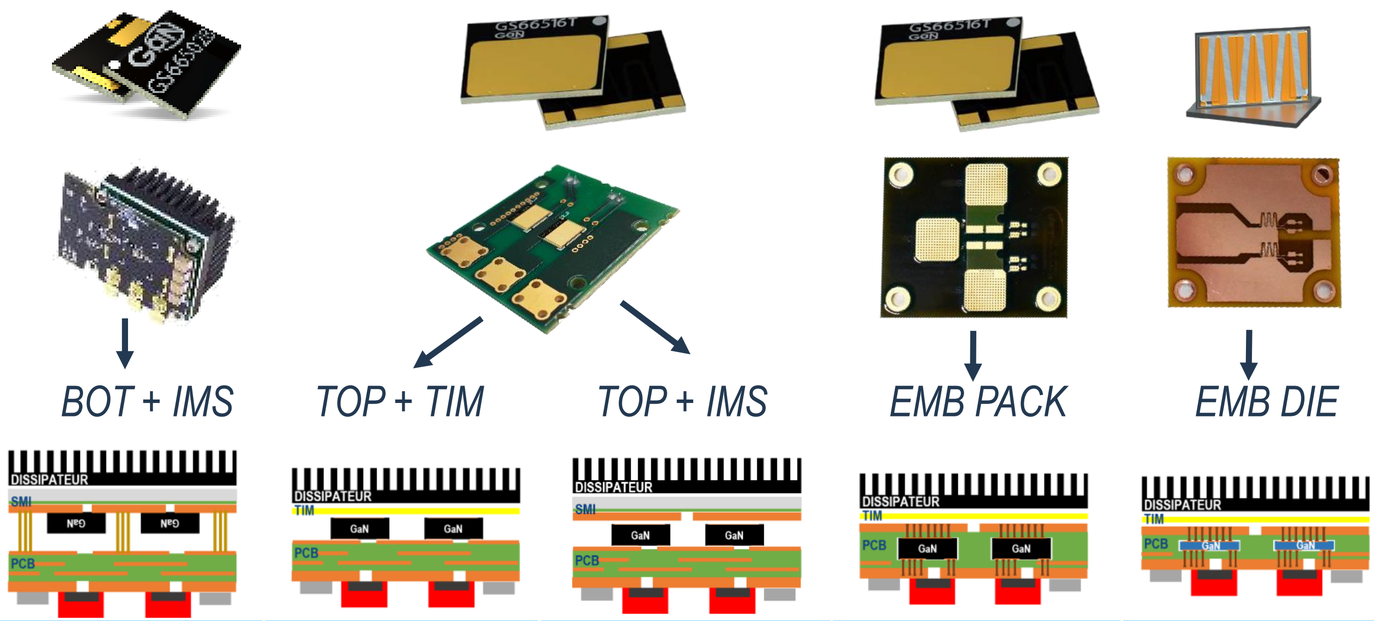
Thermal pad surface XXmm²

Copper thickness 250µm



- Very good thermal resistance
- Very low inductance

Comparison



	BOT+IMS	TOP+TIM	TOP+IMS	EMB PACK	EMB DIE
Thermal resistance	Worst	Good	Very Good	Very Good	Best
Electrical performance	Worst	Good	Good	Best	Best
Power Density	Good	Regular	Regular	Best	Best

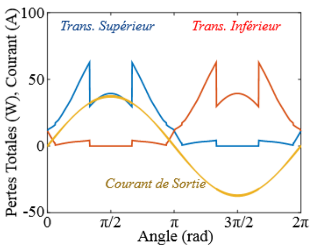
Expected

- Reliability of such packaging is one of the following subjects at IRT

Conclusions – EPowerDrive Project

- EPowerDrive project at IRT Saint Exupery proposes technologies, models and tools to increase power density and efficiency of the whole Power Drive System using WBG semiconductors (Silicium Carbide SiC and Gallium Nitride GaN).

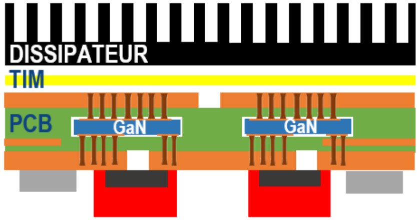
- Reliability of Power Drive Systems using SiC and GaN can be improved by reducing overvoltages, switching speed, losses and thermal cycles amplitude. Some works at EPowerDrive aim on reducing these values.



- PWM methods improve some characteristics in three-phase converters such as losses and thermal cycle amplitudes.

- Integrating capacitors inside SiC power module reduce overvoltage and losses.

- GaN embedded inside PCB reduce thermal resistance as well as overvoltage. Reliability of such “packaging” is being studied by IRT.



Thank you for your attention

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bernardo.cogo@irt-saintexupery.com