The main goal

Climate emergency

↗ Greenhouse gas emission
↗ Global temperature +1,5°C in 2 decades
↘ 60% biodiversity since 1970
7 million premature deaths annually due to air pollution
10 million hectares of forests lost annually

involvement of public authorities
evolution of standards
reforestation, bio diversity protection
eco-conception
Net Zero Emissions Targets

Collective Awareness

Needs inflation

9.7 billion people in 2050
↗ 50% global energy demand in 2050
↗ 100% electricity demand in 2050
New transportation
New materials
New energy sources
AI

Our future hinges on innovation and collaboration.

Sources : international Energy Agency, Bloomberg NEF, International Council of clean transportation

Advanced SiC Inverter: A Powerful Tool for Electrical Motor Characterization and Optimization

Alexandre BATTISTON, IFPEN
Idir ARSLANE, CRITT M2A

AVL SET's Symposium,
19/09/2024

AGENDA

- Context & Objectives
- Foundations and Technology
- Applications
- Experimental Results
- Conclusion

Speakers

Alexandre BATTISTON

Specialty : Electrical Engineering
Current Position: Research and Innovation Project Leader (Advanced Power Electronics)
Company: IFP Energies Nouvelles, Rueil Malmaison, France
Education: PhD degree from the University of Lorraine, in 2014, Nancy, France
Thesis: "Modeling, control, stability, and implementation of impedance source inverters. Application to embedded systems."
Previous Positions:

- 2016 - 2023 : Power electronics engineer, IFPEN, Rueil-Malmaison, France
- 2015 - 2016 : Design engineer in power electronics converters, Mavel SRL, Pont-Saint-Martin, Italy
- 2011 - 2014 : PhD Student and Teaching Assistant at University of Lorraine & IFP Energies nouvelles

Skills: Electrical Engineering; Power Electronics; Inverters, Stability, Control

IFPEN

A major research and training player in the fields of energy, transport and the environment.

Established : 1944

Locations :

- Rueil-Malmaison (Paris), France
- Solaize (Lyon), France

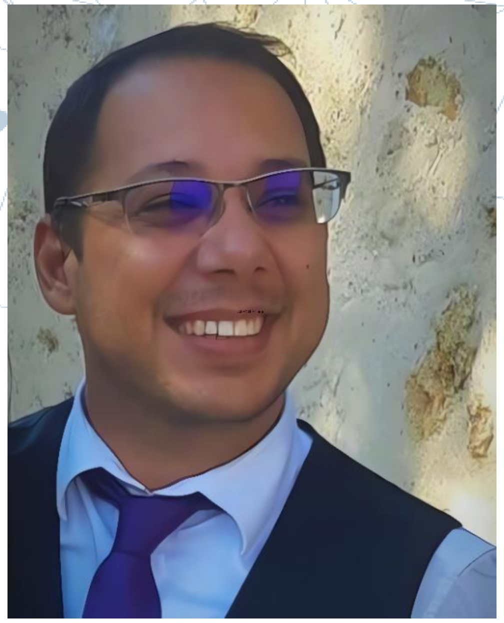
Industrial field :

- Scientific concepts
- Fundamental research
- Technological solutions in the context of applied research.

Main Areas :

- Climate, environment, and circular economy
- Renewable Energies
- Sustainable Mobility
- Responsible oil and gas

Speakers



Idir ARSLANE

Specialty: Electrical Engineering
Current Position: R&D engineer in Power Electronics, Power HIL specialist at CRITT M2A
Company: CRITT M2A, Bruay-la-buissière, France
Education: Research Master degree from University Lille1 Technology & Science, France
Previous Positions:

- 2018 – 2023 : Electrical R&T Laboratory Manager at Safran, Yvelines, Île-de-France, France
- 2015 - 2018 : Power Electronic R&D Laboratory Manager at Renault, Yvelines, Île-de-France, France
- 2014 – 2015 : Power HIL Engineer at Renault, Yvelines, Île-de-France, France
- 2012 – 2013 : Power HIL Engineer at L2EP, Lille, France

Skills: Electrical Engineering; Power Electronics; MATLAB/Simulink, Power HIL, RT emulation

CRITT M2A

An Independent research center in testing and R&D for electromobility. Provide advanced testing and R&D services to support the energy transition and optimize energy management.

Established: 2000

Location:
- Bruay-la-buissière, France

Industrial field :
- Expertise
- Technological solutions in the context of applied research.
- Production, end of line

Main Areas :
- Battery Testing (cells, modules, packs)
- Abusive and Regulatory Testing (short-circuit, fire, vibration)
- Inverter Testing
- Powertrain Testing
- Turbocharger Testing

Context & Objectives

Context & objectives

Some key figures

+ 60 %
EV car sells by 2030

+ 500 B$
EV infrastructure investment by 2040

+ 27 %
Electricity demand due to e-mobility transition by 2050

Some challenges

- Better efficiency
- Better thermal management
- Less components/ materials
- More sustainable energy
- Zero emission
- More safety
- Less noise
- More accurate control
- Battery optimization & protection
- Connected vehicles
- Automated driving
- New materials
- AI
- New power control strategy
- New power conversion architectures

A possible answer

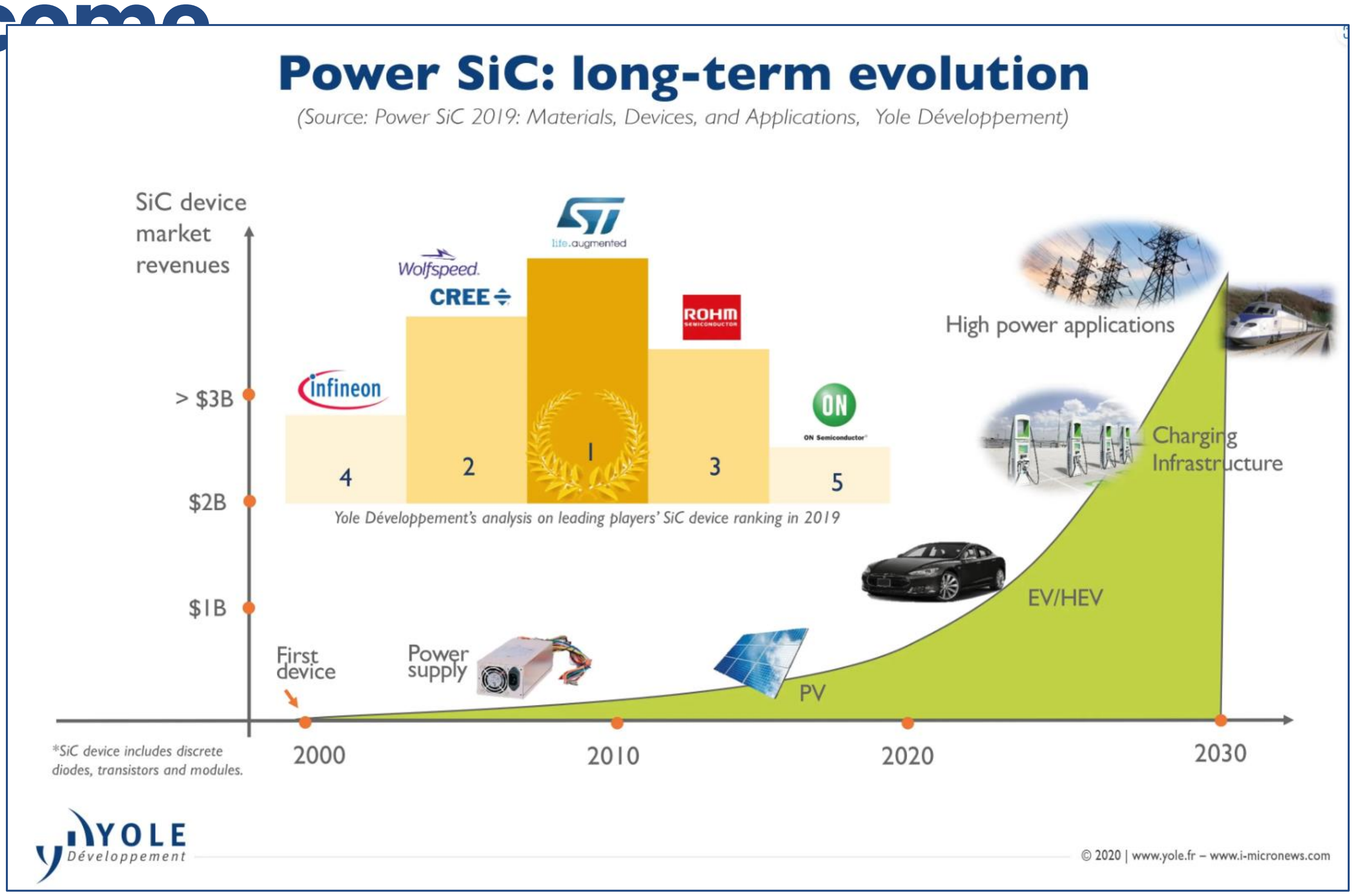
Power electronics development for designing and testing new products

Context & objectives

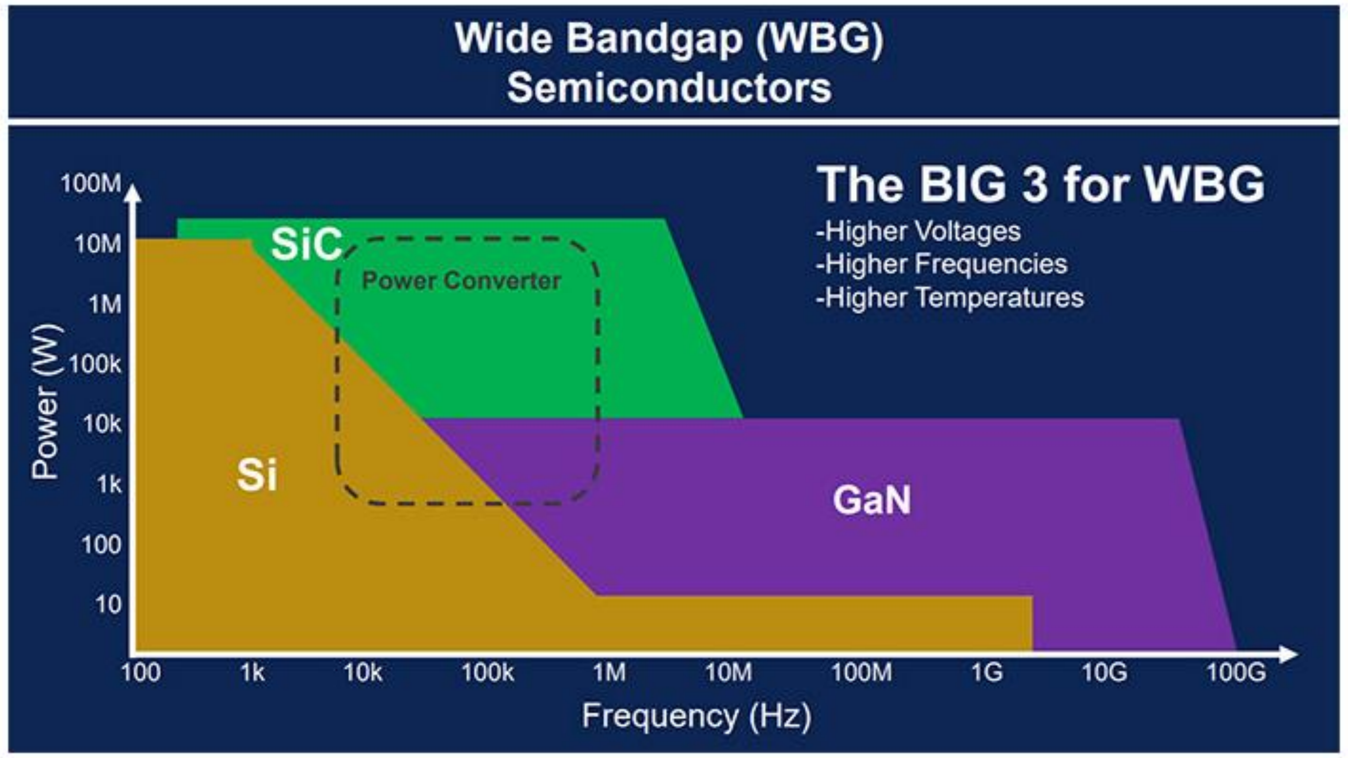
Power electronics is experiencing a major change with the adoption of WBG devices

- Excellent performance benefits
- Enhanced physical properties

Scientific & technical locks are now greatly addressed or going to be overcome



Power inverter applications according to the semiconductor's technology



Source KEMET

The BIG 3 for WBG

- Higher voltages
- Higher switching frequencies
- Higher temperatures

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Context & objectives

Ideas + knowledge + expertise

Awareness of the market, of the test needs

Research project collaboration / integration

Developing an adaptative & versatile inverter for testbench applications

Foundations & technology

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Technological Innovations

A versatile 800V – 3Ph inverter for test bench applications

- High-power and efficiency, up to 50 kHz switching frequency
- Speed, torque, current & voltage control for high performance applications
- Free-wheeling and active short circuit protections for safe bench application
- Silicon Carbide Technology

Specifications

Peak power	320 kW
Continuous power	250 kW
Nominal input voltage	750Vdc
Maximum DC current	350 Adc
Maximum output current	750 Apk (500Apk continuous)
Switching frequency	10 - 50 kHz
Technology	Mosfets Full-SiC
Peak efficiency	99% on wide area
Weight	15,7 kg

Inverter commercialized by the French SME Alphée

https://alphee.engineering/

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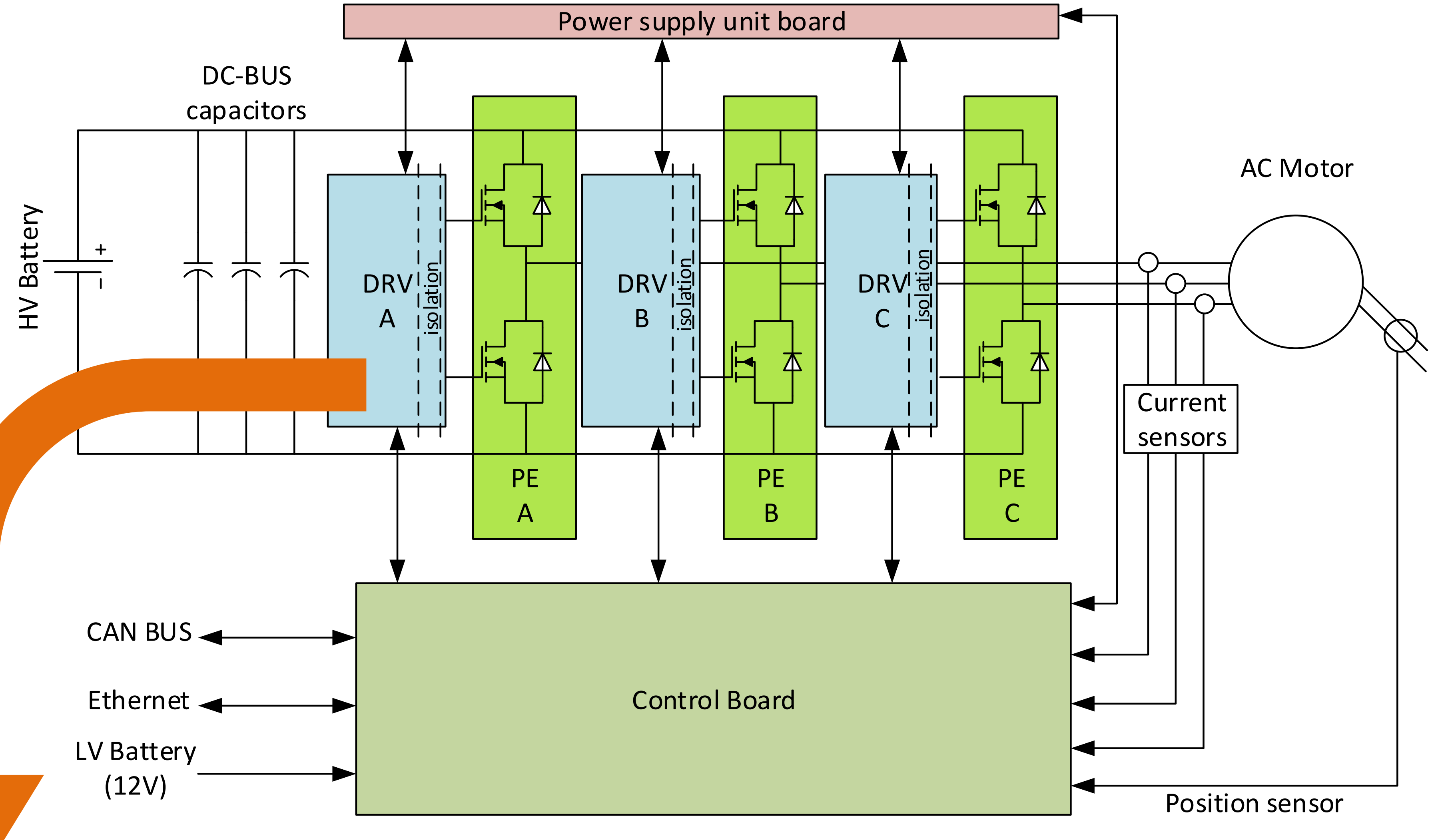
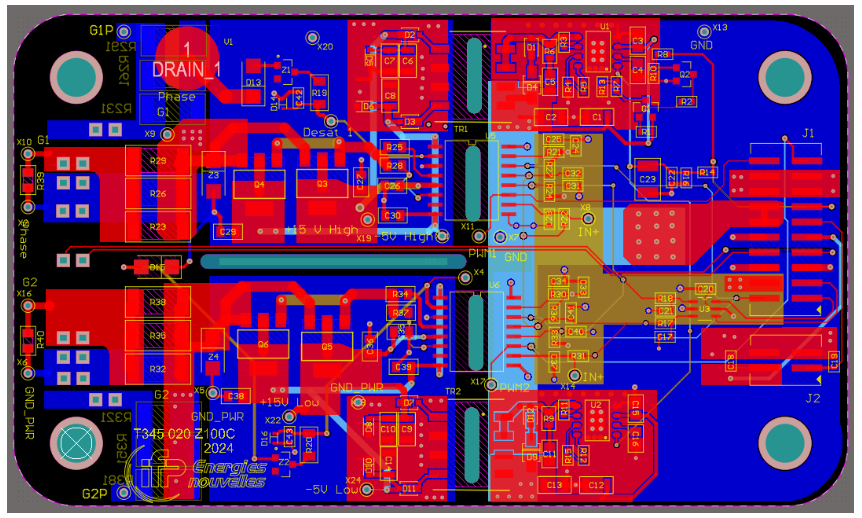
Technological Innovations

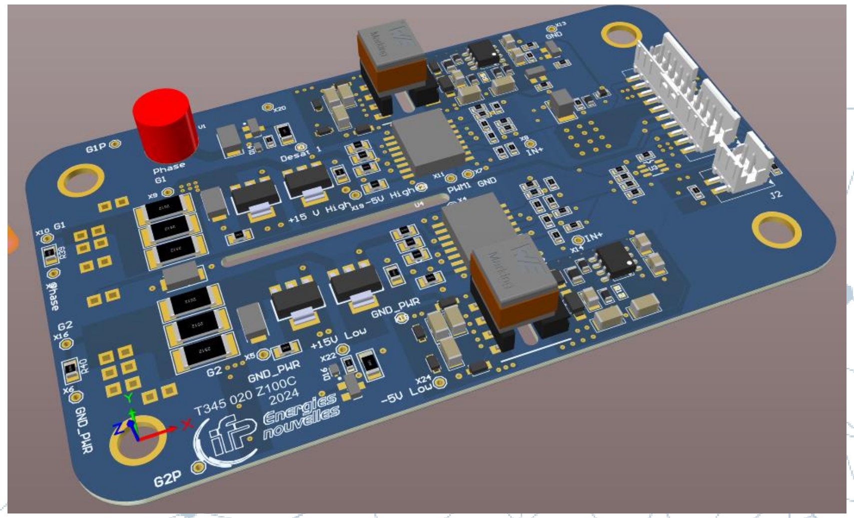
The design
based on a 2-level topology with mechanical integration

- Implementation of SiC power modules
- Design and manufacturing of Gate Drivers board (DRVA, DRVB, DRVC) and associated power supplies
- Design and manufacturing of DC-bus laminated busbar
- Integration of an IFPEN control board
- Thermal calculations and validations
- Mechanical housing design





Electronic CAD



3D board

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A. BATTISTON, L. Kefsi, M. Milosavljevic and A. Sabrie, "High-Power / High-Voltage (250 kW / 750V) SiC-Based Inverter for Electric Vehicles Applications," *2021 23rd European Conference on Power Electronics and Applications (EPE'21 ECCE Europe)*, 2021, pp. 1-11.

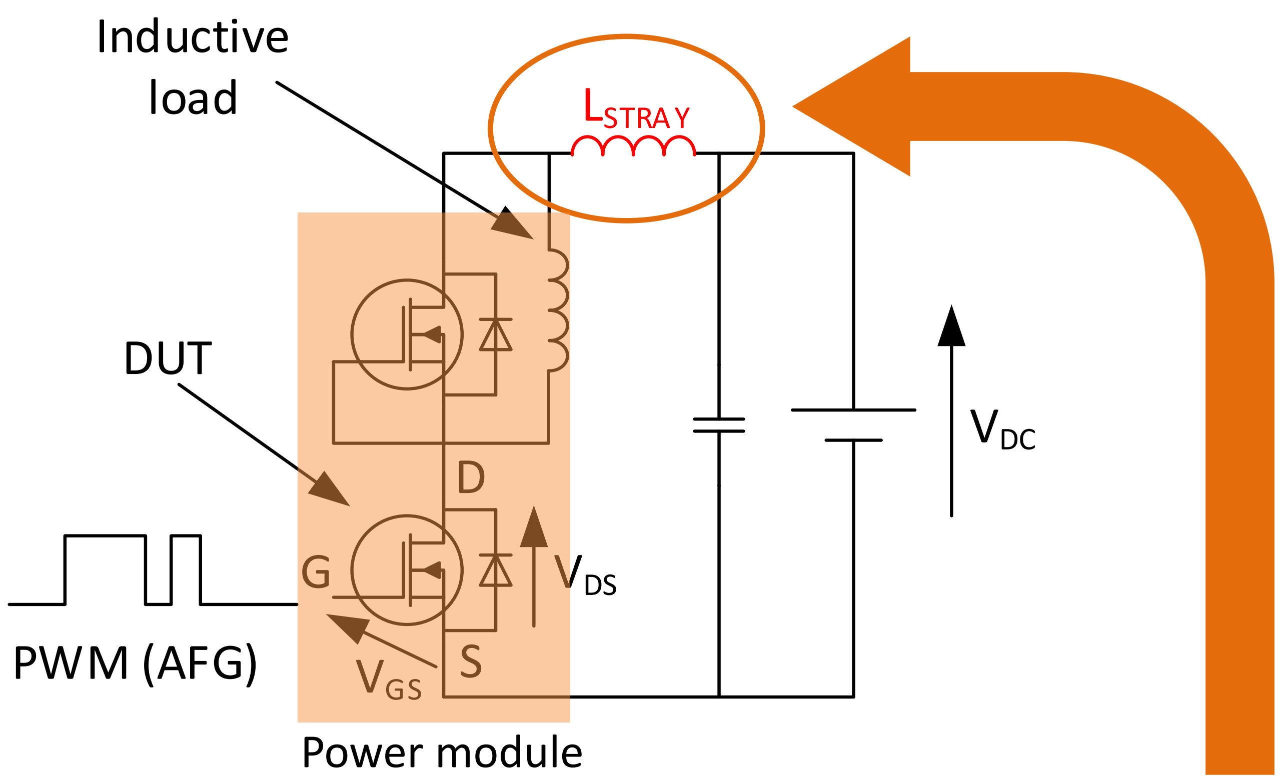
Technological Innovations

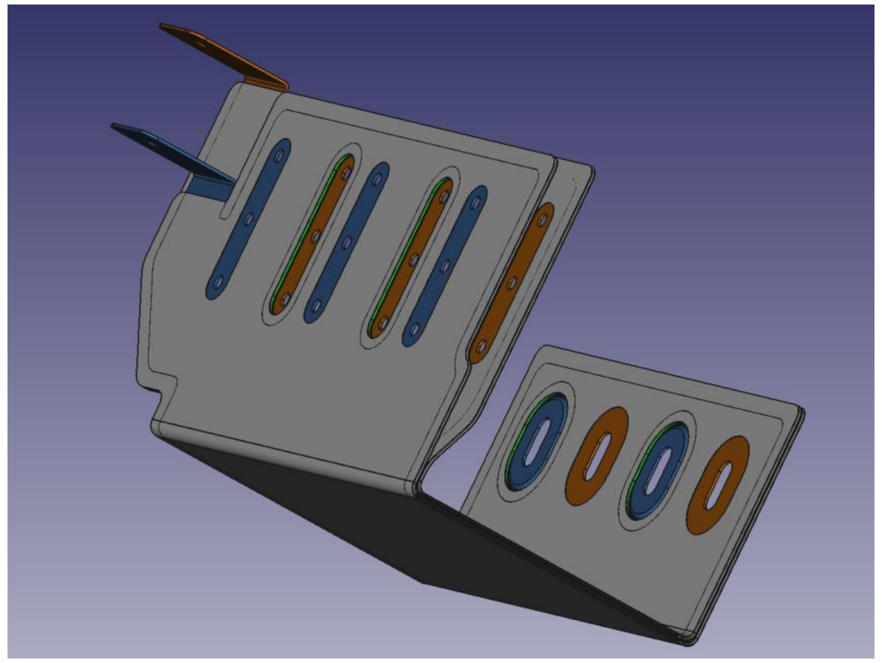
Laminated DC-link busbars
for high performance and reliability operations

- Reducing parasitic inductance (Lstray) leads directly to a reduction in the overvoltage at the turn-off of SiC devices

- Parasitic inductance is assessed using finite elements analysis (FEA)

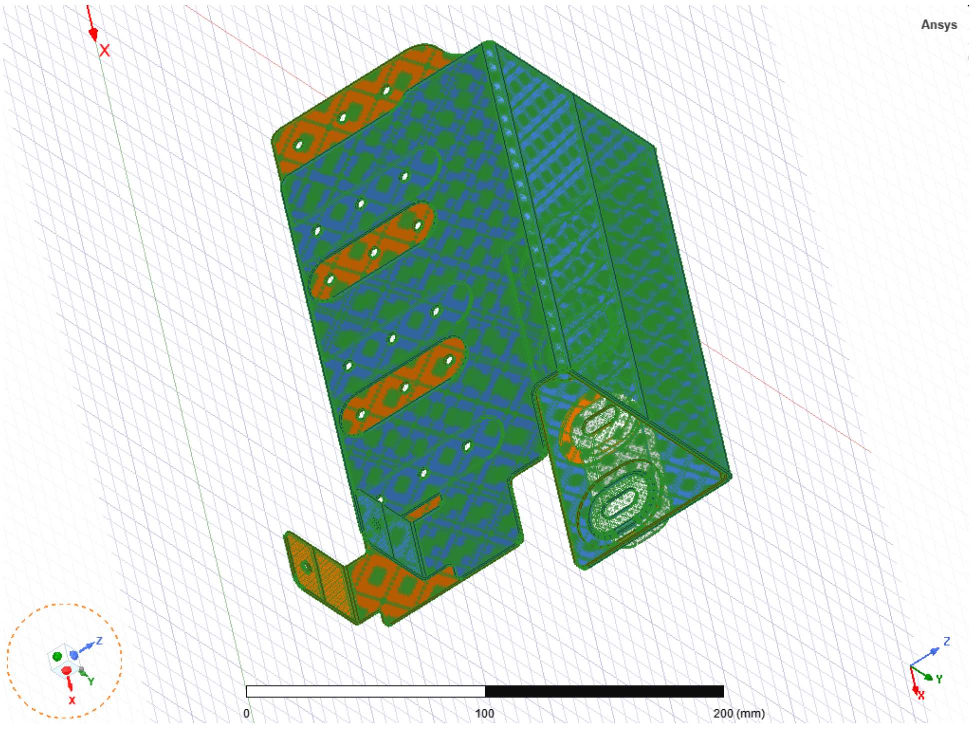
Parasitic extraction





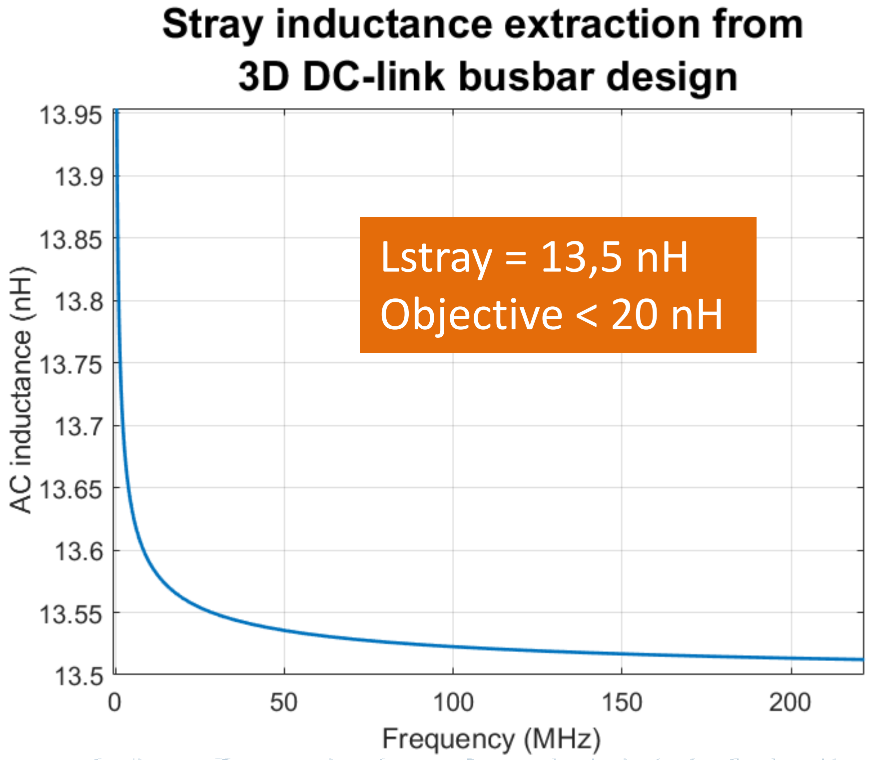
DC-link busbars 3D mechanical design

FEA



Meshing and calculations

Parameters extraction



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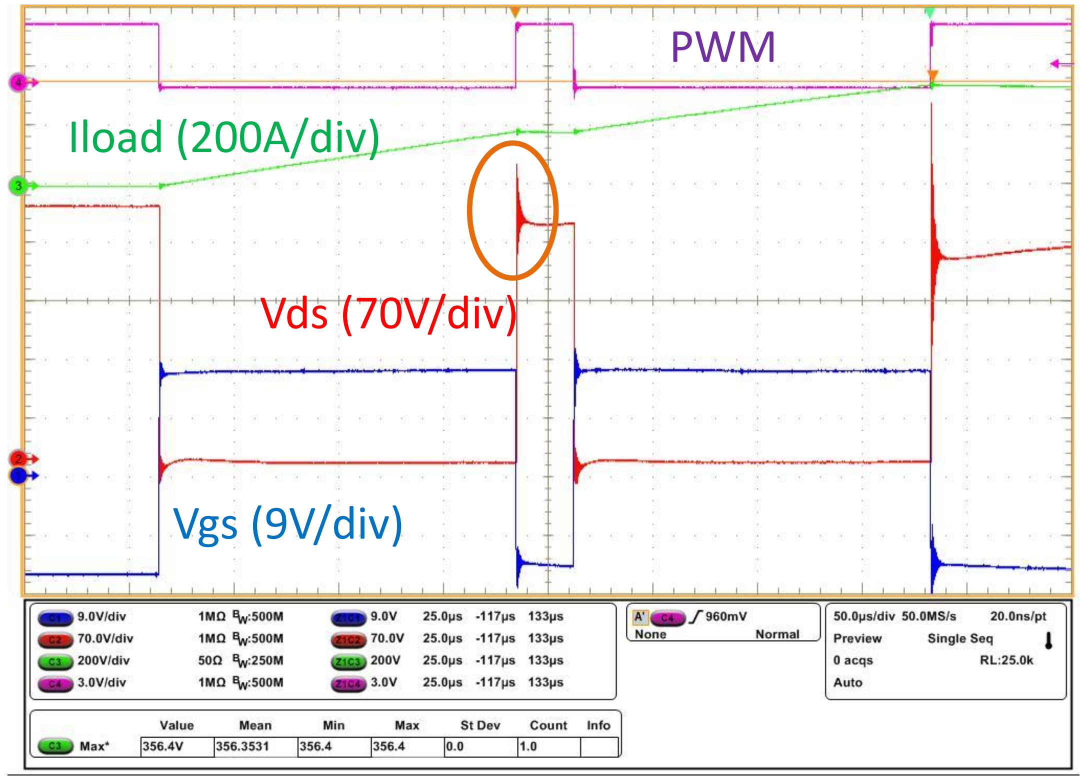
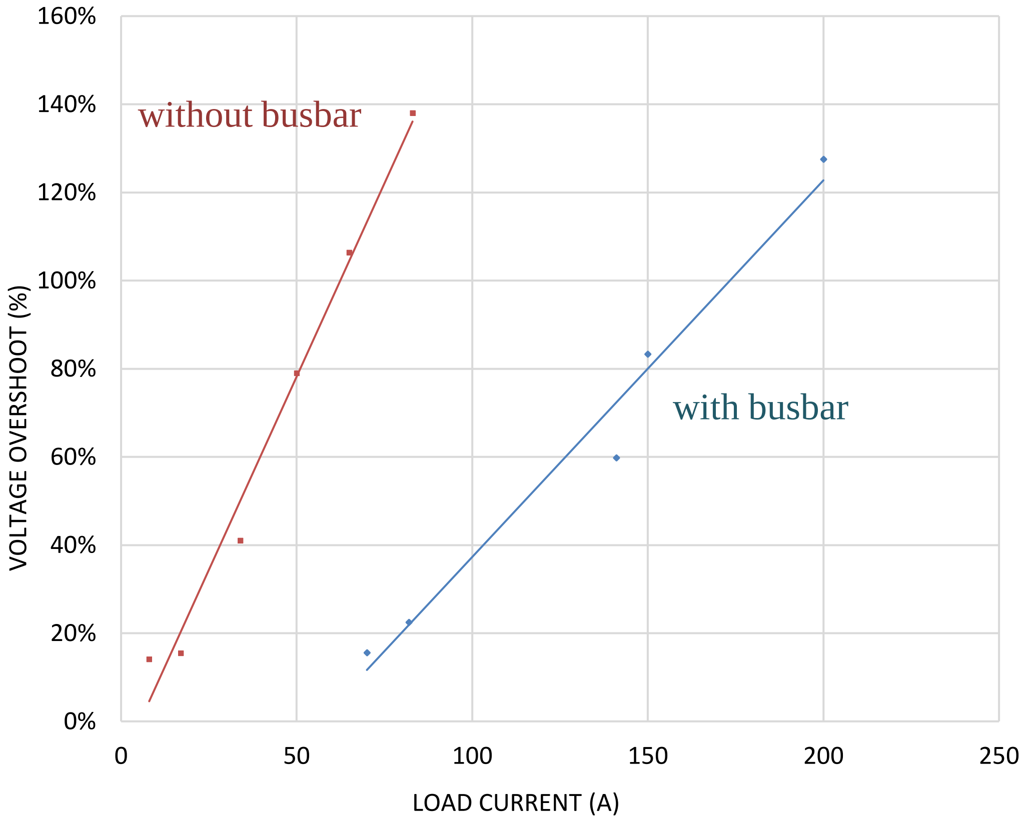
Technological Innovations

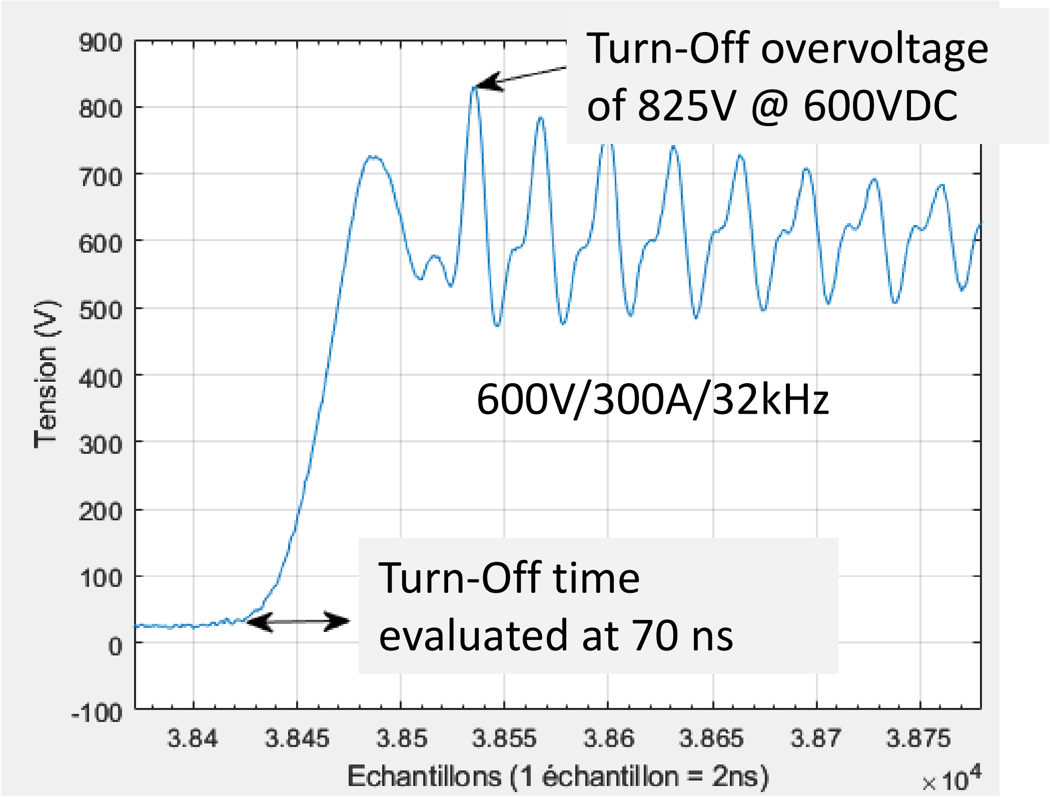
Laminated DC-link busbars for high performance and reliability operations

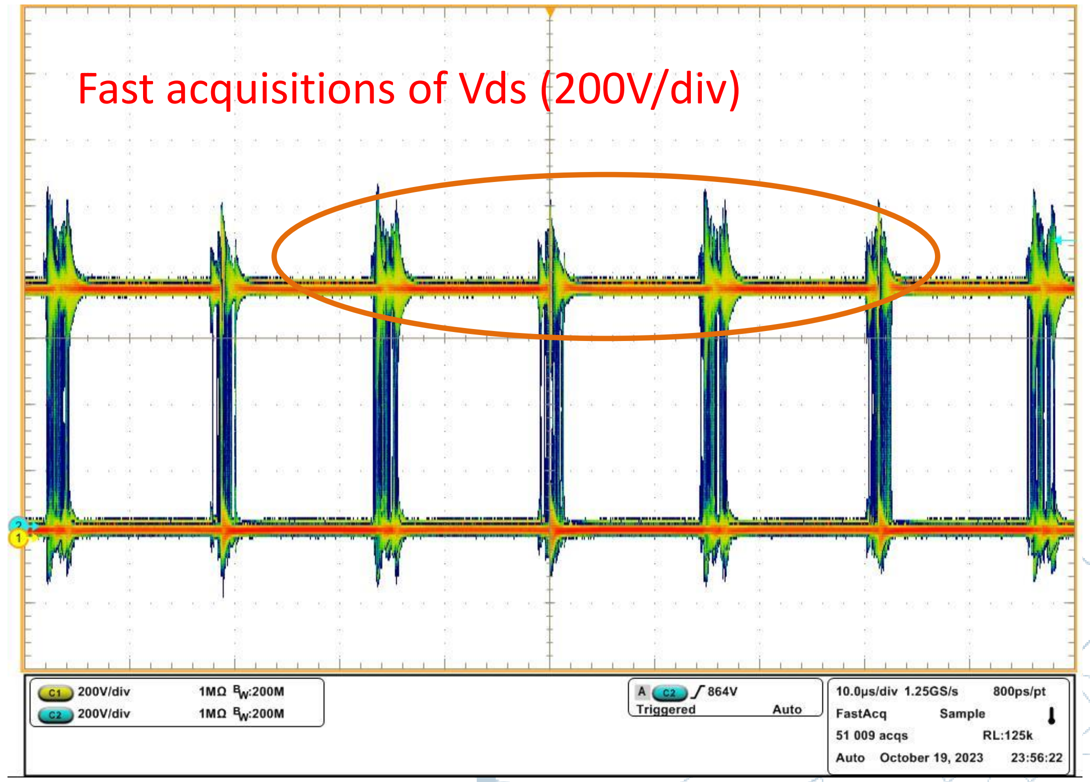
- Overvoltage evaluation at turn-off by two methodologies
  - Double pulse test (DPT)
  - Power cycling test (PCT) on AC sinus load



Overvoltage evaluation (DPT) @ 300V, 400A





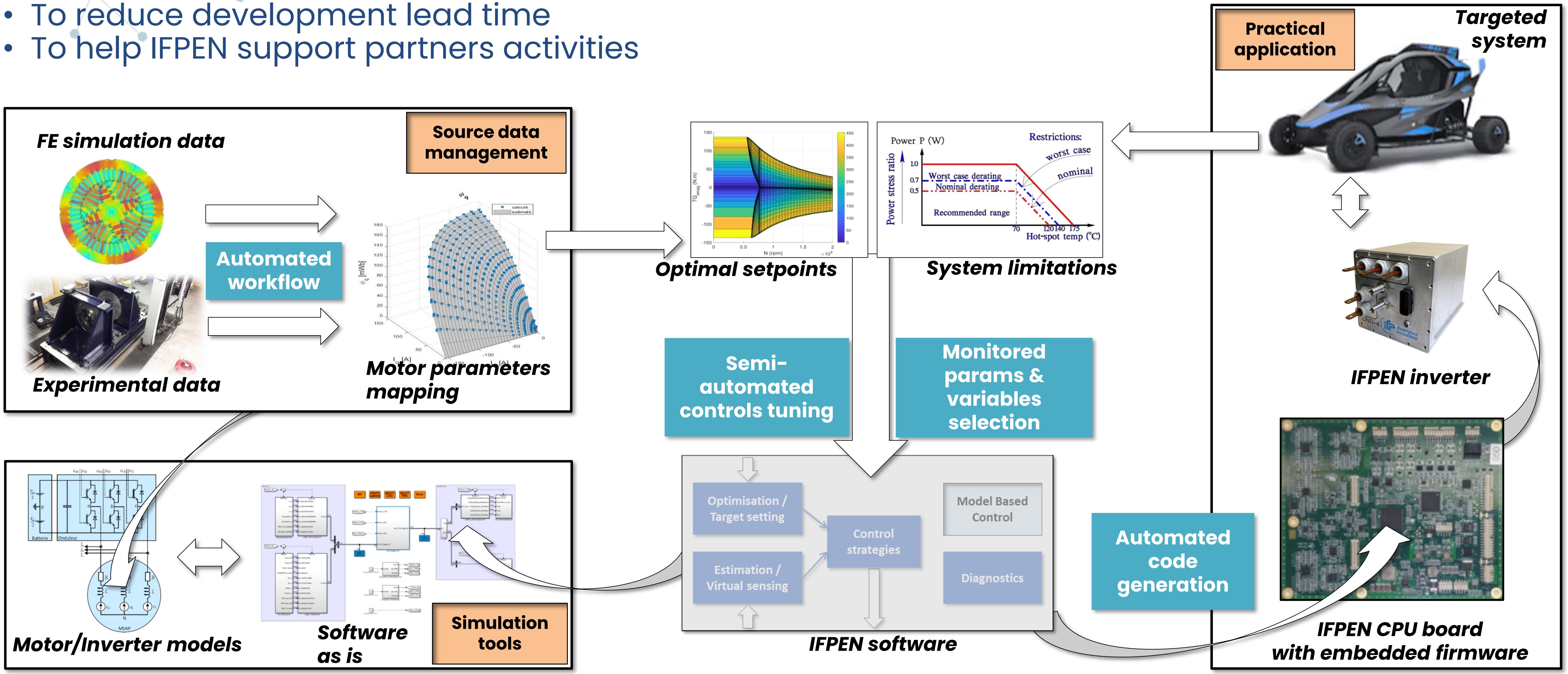


Overvoltage evaluation (PCT) @ 700V, 400A

Technological Innovations

IFPEN developed a Full Control Toolchain for e-Drives

- To reduce development lead time
- To help IFPEN support partners activities



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Applications

800V – 3Ph inverter for test bench applications

- A hardware and software versatile solution completed with a full control toolchain for e-drive

- Able to drive several motor topologies such as
  - Permanent-magnet synchronous motor (PMSM)
  - Permanent-magnet assisted Synchronous Reluctance Motor (PMA-SynRM)

- A versatile solution for testing and characterizing electrical motor up to their performance and thermal limits with an advanced control

The RedHat project

RedHat ?

REliability and High Torque and power density motor

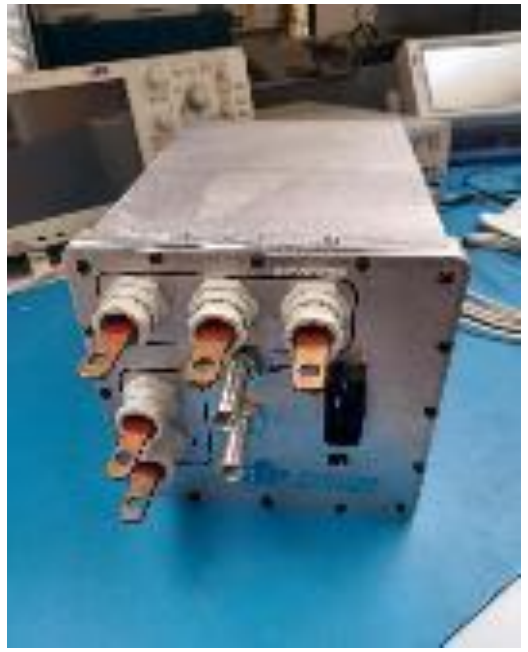
Objectives

Efficiency of electromechanical conversion chains,
Improve the torque and power density of powertrains,
12 kW/kg and 12 Nm/kg

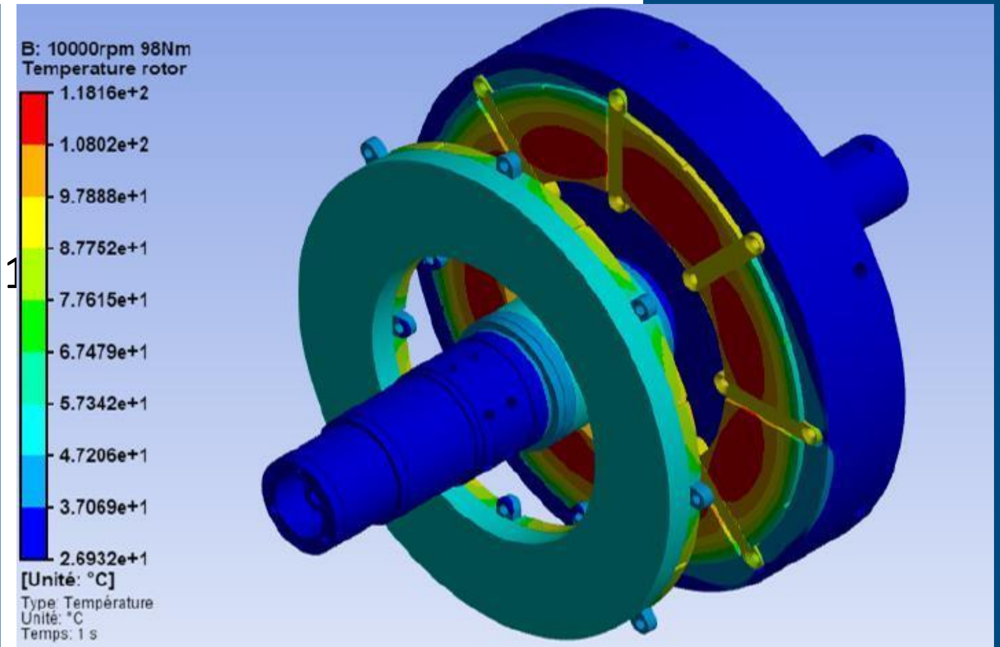
The electrical machine

Axial flux PMSM, compact
Surface-mounted permanent magnets (SmCo)
Dual rotor
Pole pair: 4 / Number of teeth: 12
Max mechanical power: 188 kW
Max torque: 183 Nm
Max speed: 10,000 rpm
Specific power: 12 kW/kg
Liquid cooling in the rotor and stator
Innovative in the shape of the laminations
Innovative in the choice of materials

Consortium



IFPEN SiC inverter



RedHat PMSM axf

Experimental results

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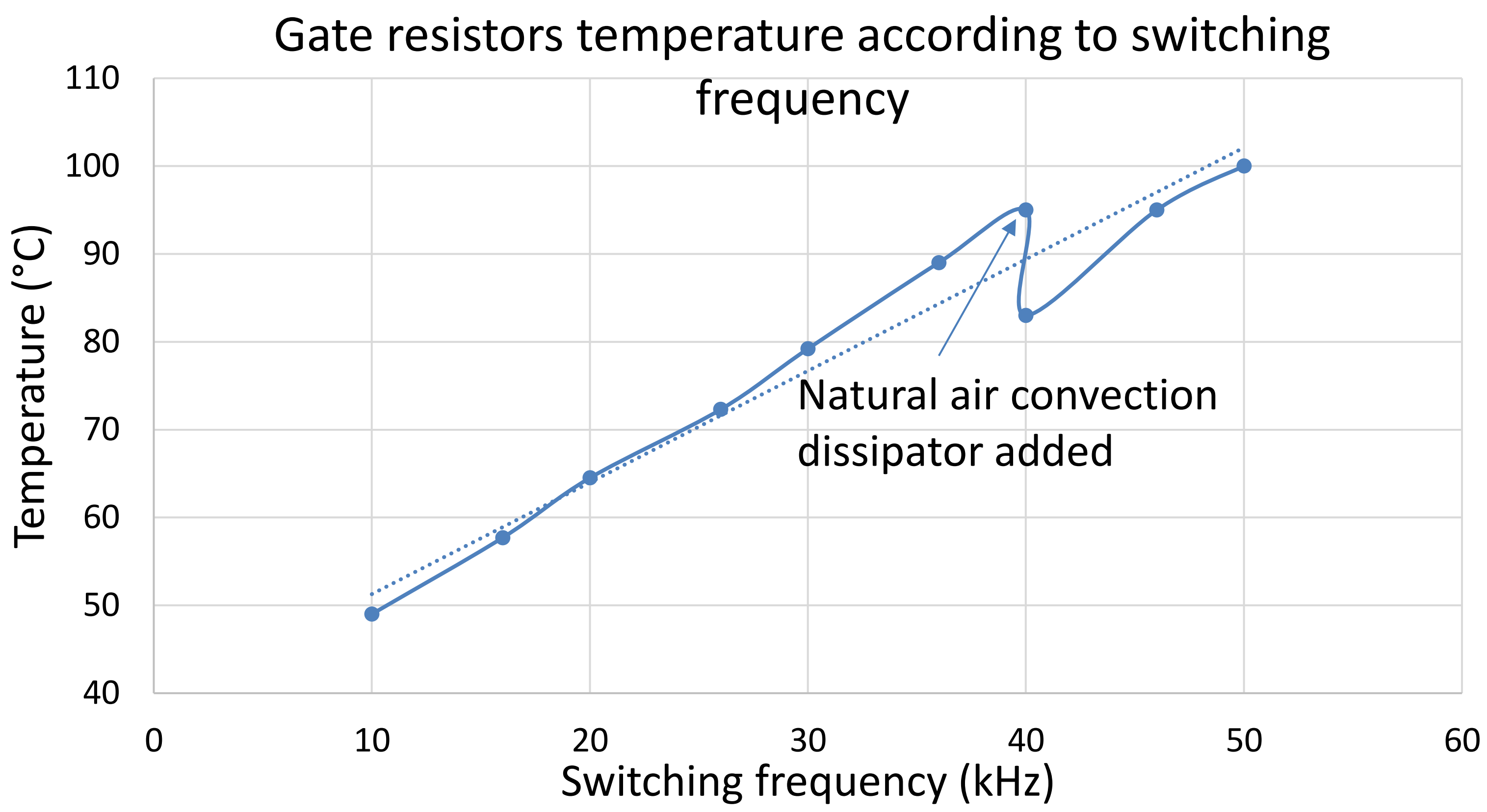
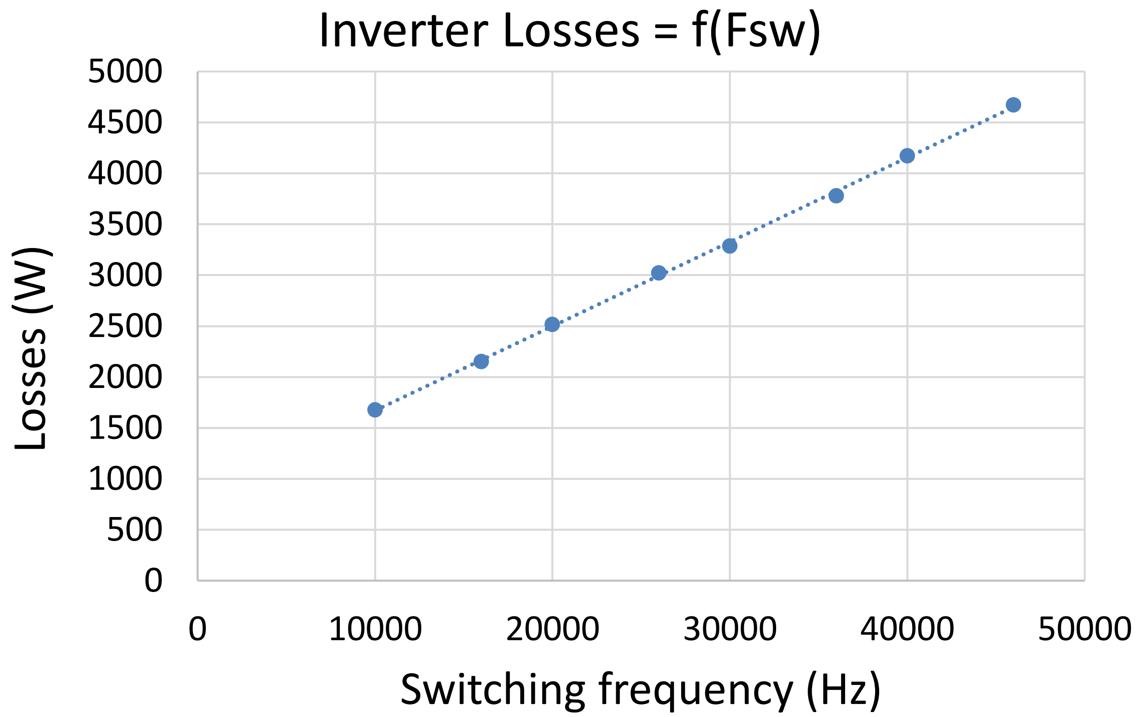
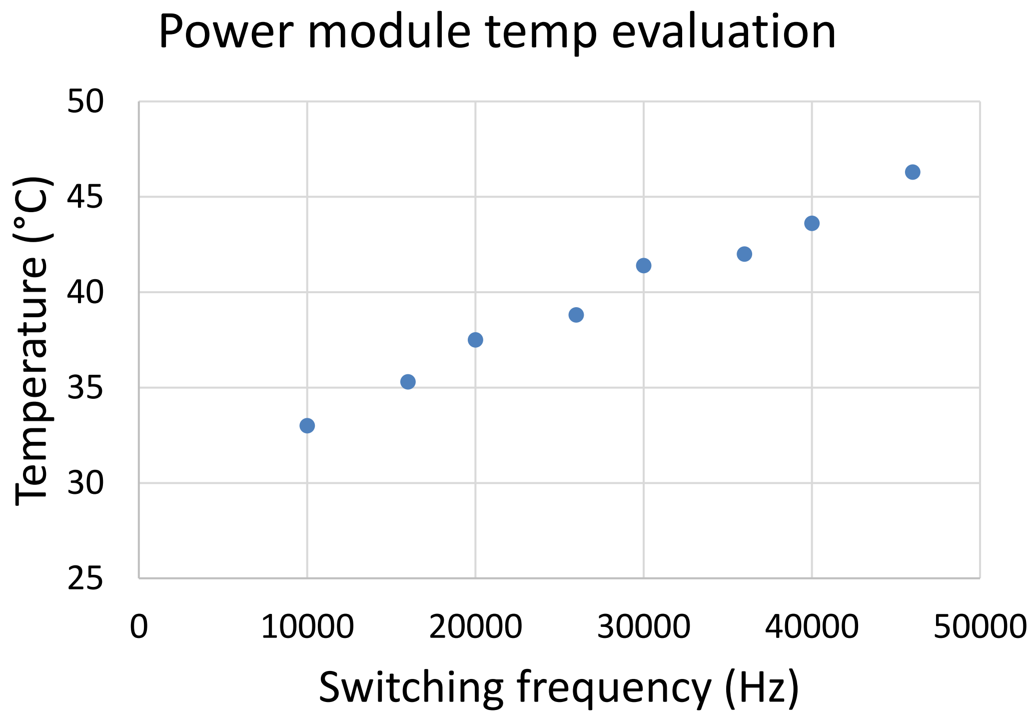
High frequency operation

High switching frequency operations

- Gate drivers design to operate @ Fsw = 50 kHz
- Gate resistors accordingly chosen to allow
  - High slew rate (dv/dt) & reduced switching losses
  - High switching
- Evaluation of inverter's losses according to Fsw and thermal assessment







Gate resistors IR thermal measure @ Fsw = 50 kHz

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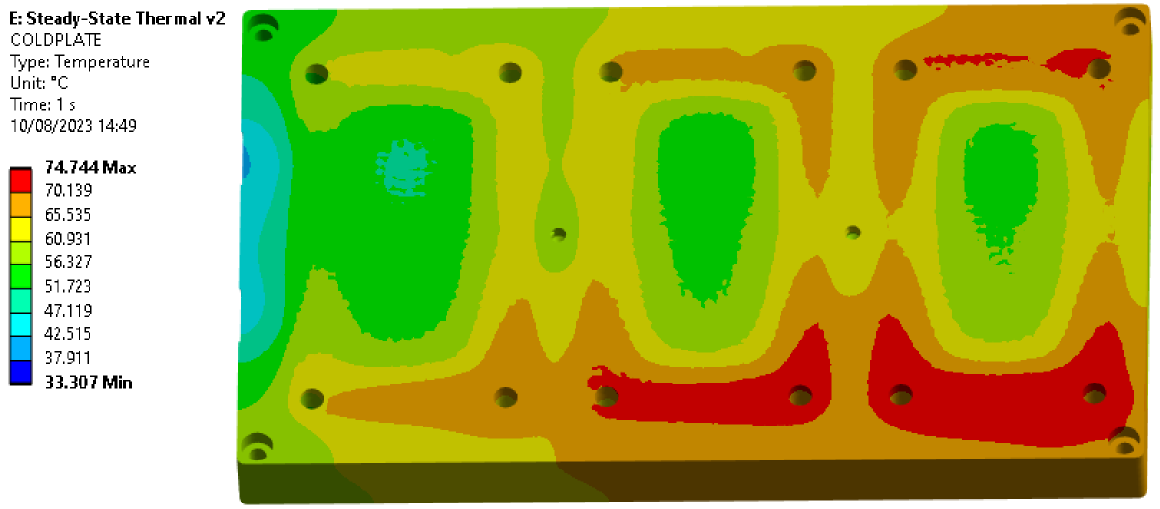
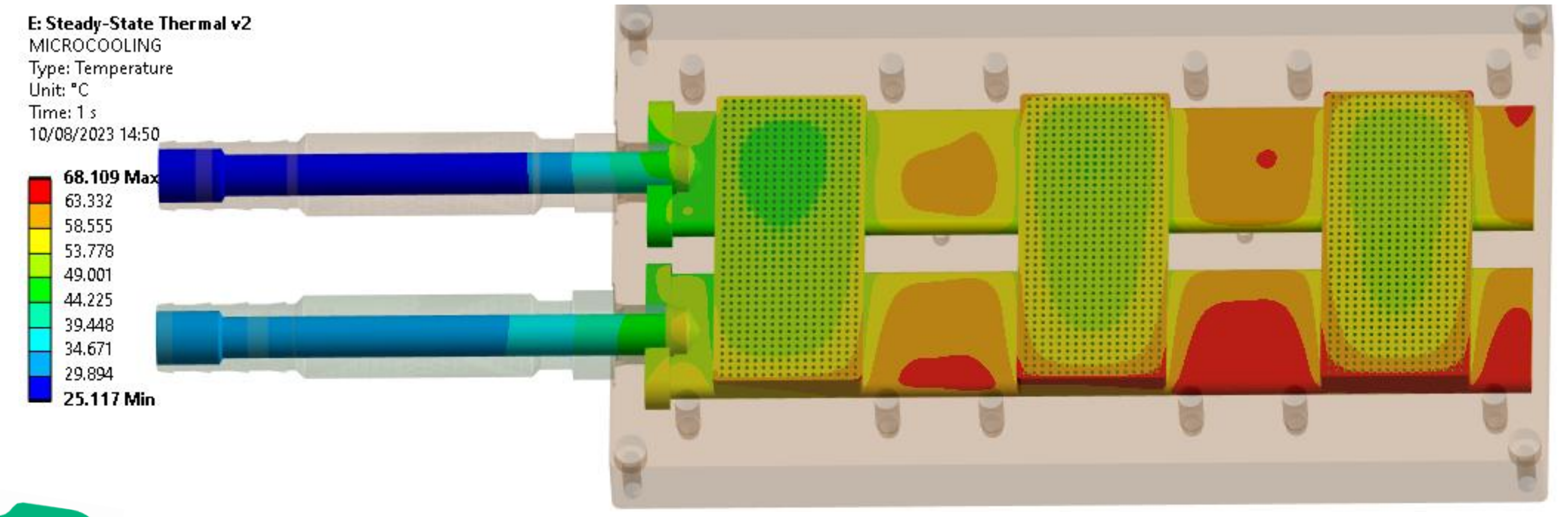
Thermal analysis and validation

Thermal analysis

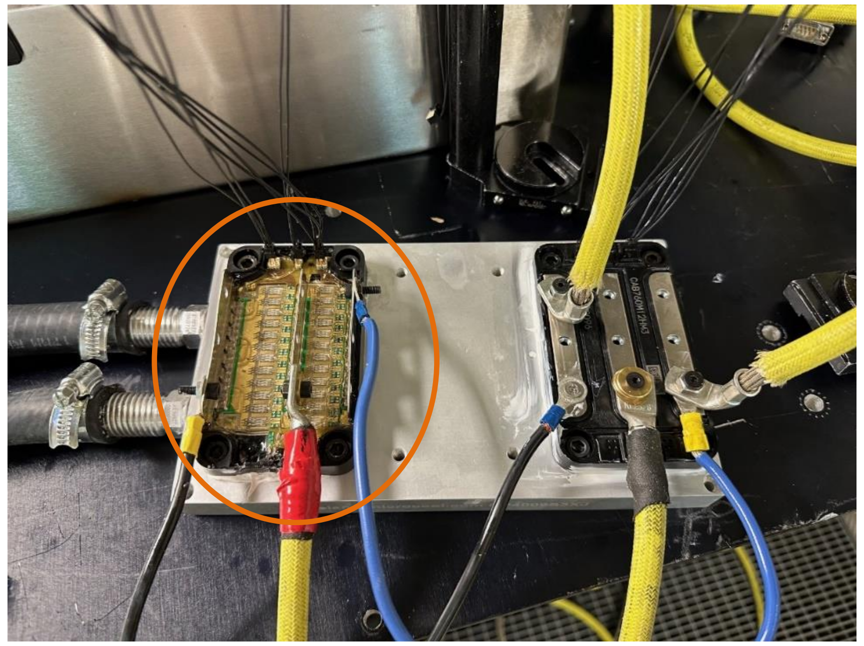
- 3D FEA simulations
- Evaluation of performances of the cold plate at the maximum power module losses
- Dedicated Power Cycling Test (PCT) bench for evaluation of the thermal behavior of power modules (open module)



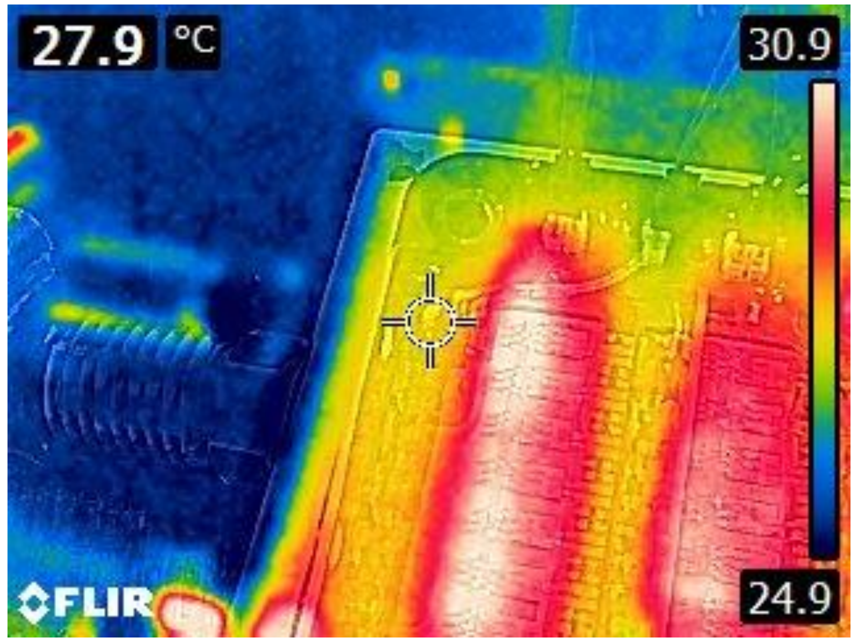
Good thermal distribution around the modules

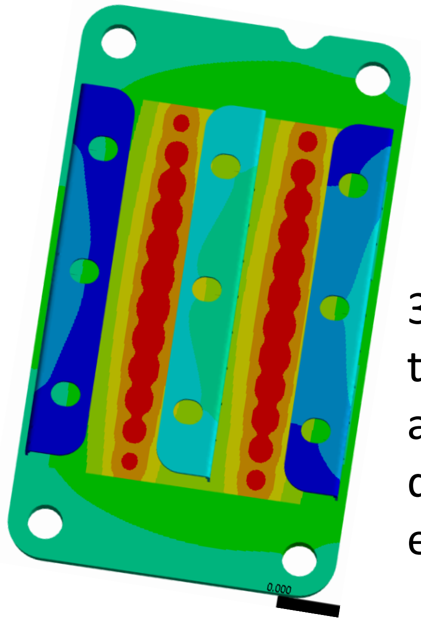


Validation of water/glycol cooling system performance at 10l/min



Open module on cold plate for thermal assessment





3D power module thermal modeling according to datasheet & experimental data

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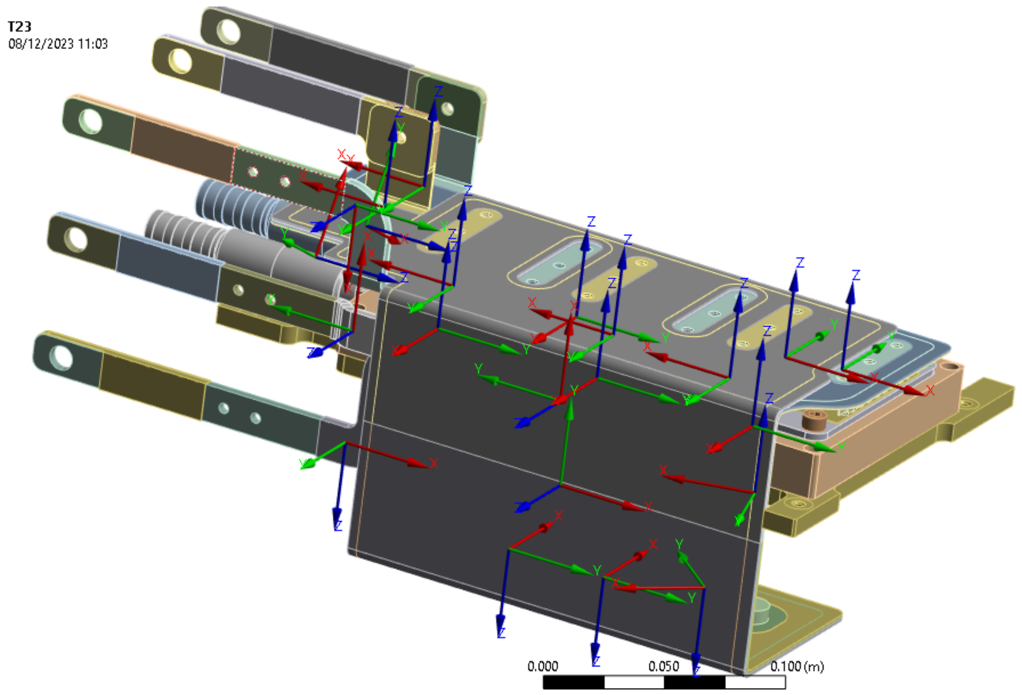
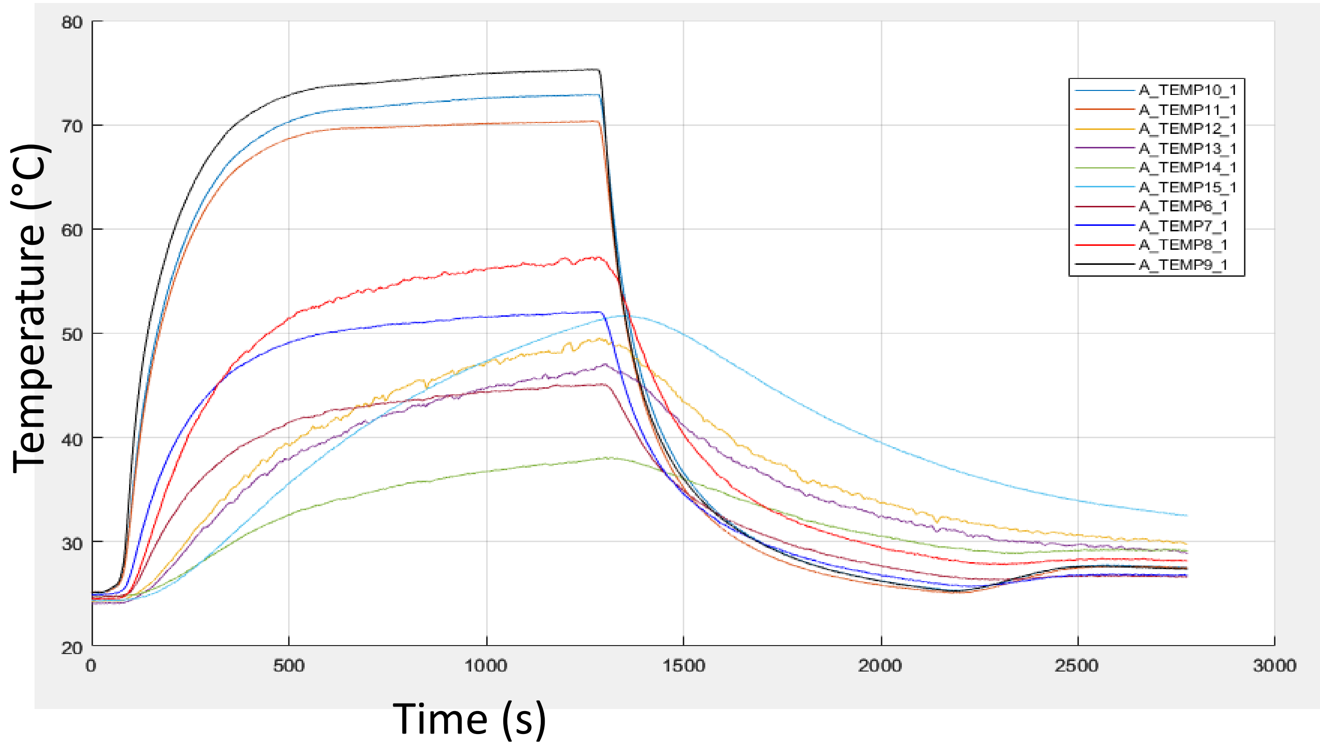
1st power validation phase

Continuous power validations – thermal validations

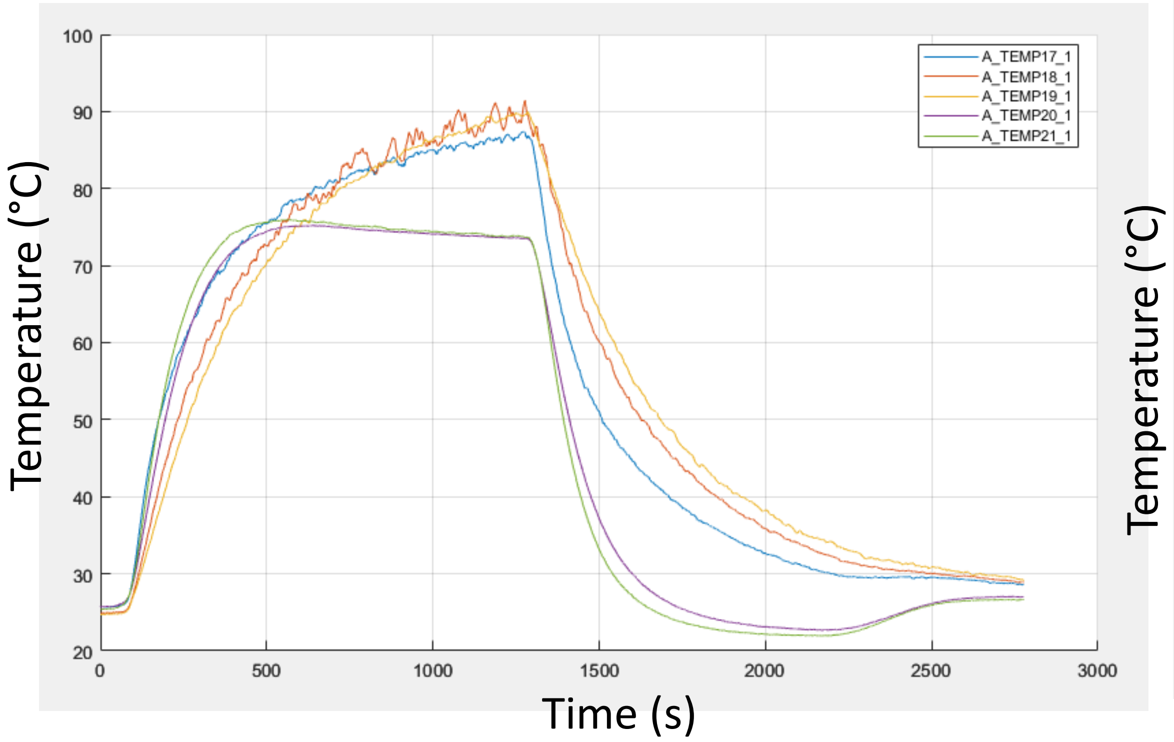
- Inverter fully instrumented with thermocouples
- Evaluation on inductive load (AC performances validations)
- Example of operating point: Vdc = 600V, Iph = 500Apk, Fsw = 30 kHz, T°C cooling = 25°C



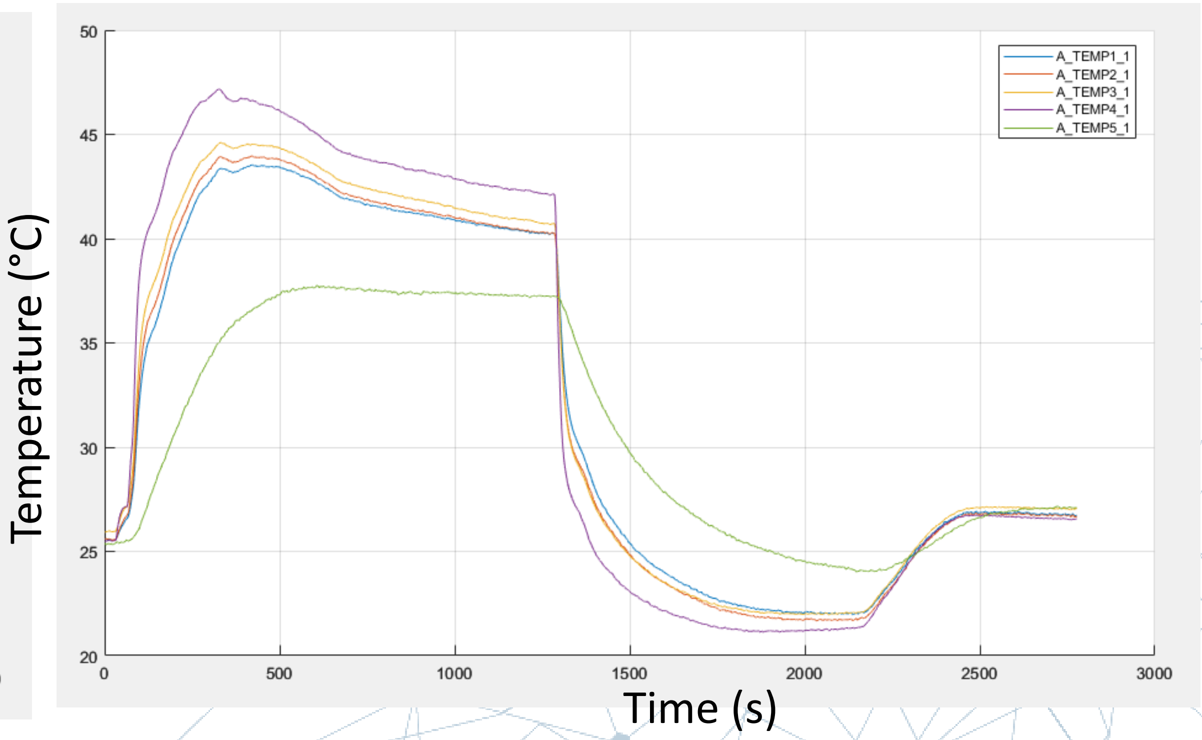
DC-bus thermal results



AC-busbars results



Cold plate thermocouples results



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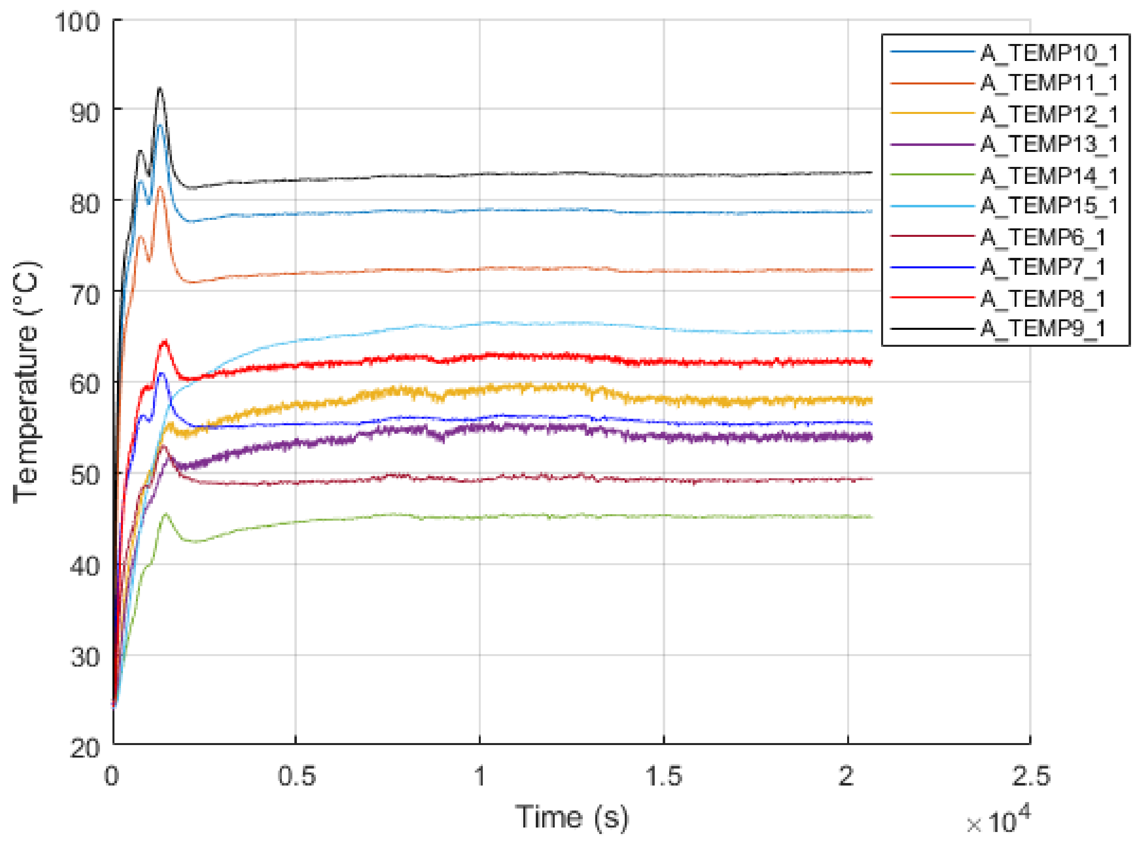
1st power validation phase

Continuous power validations – thermal validations on inductive load (L)

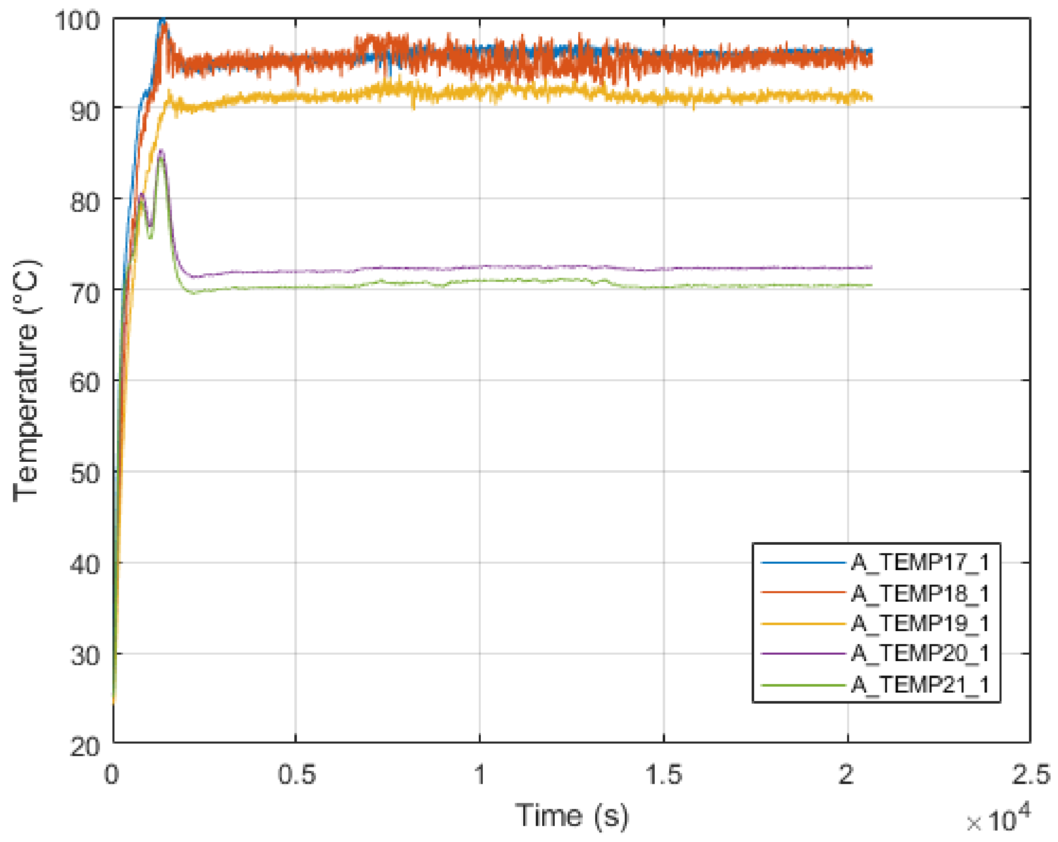
Example of continuous operating point results (more than 5h operation) :

- 600 Vdc
- 500 Apk
- 30 kHz
- Tcooling = 25°C

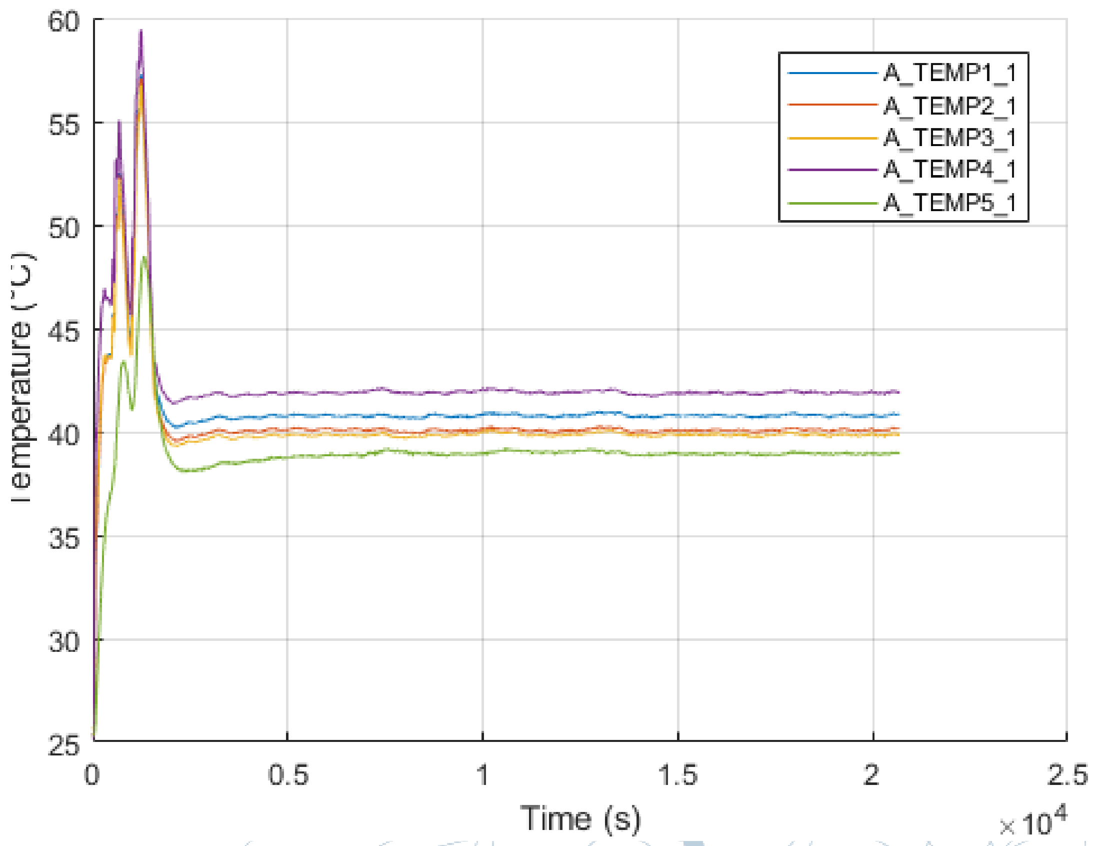
DC-bus thermal results



AC-busbars results



Cold plate thermocouples results



2nd power validation phase

AVL inverter testbed :

DC bus emulation

E-STORAGE

P_{max} = 320 kW
U_{max} = 1000 V
I_{max} = 800 A

Emulation of DC sources

DC

Temperature & humidity

Climate chamber

T : -40°C à +90°C
HR : 5% à 95%

Liquid cooling system

T° : -50°C à 220°C
Flowrate : 120 L/min

AC3

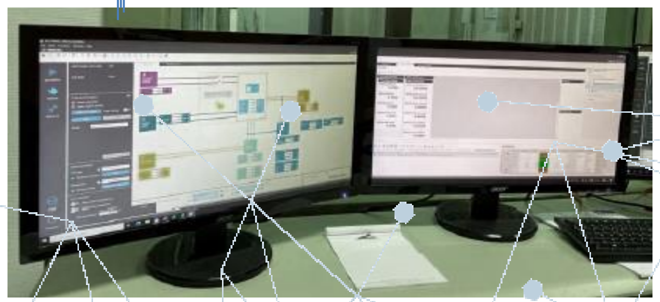
Electrical machine emulation

EME

3 phases
P_{max} = 320 kVA (AC or DC)
$U_{ph\text{-}ph}$ = 735 V
$I_{ph\text{-}max}$ = 400 Arms

Electrical machine emulation
Speed/position sensor emulation

CAN
Ethercat
TCP / IP



AVL PUMA II
(PUMA INVERTER)

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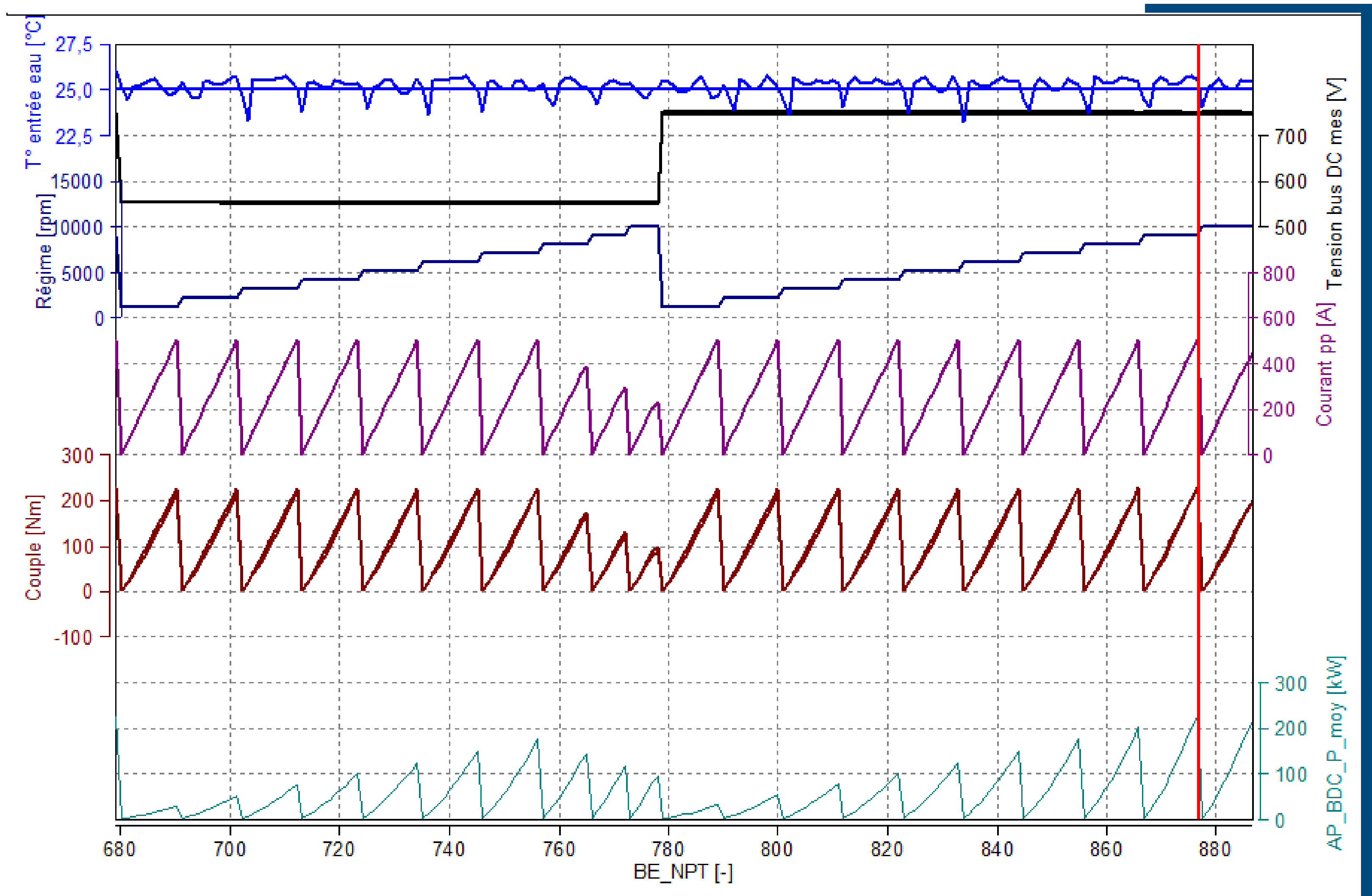
Automated test sequences*

References ranges : inputs

Inner cooling temperature °C	25;65
DC Bus voltage (V)	550;750
Speed (rpm)	[0:1000:10000]
Phase peak current	[0:50:500]
Switching frequency (kHz)	26 ; 30; 40; 42



Measurements : outputs

Internal temperatures (°C)	[24,3 : 106,5]
Efficiency max (%)	98,6 (@226,7Arms; 550Vdc; 93,4 kW; 30kHz)
Pdc max (kW)	224

Additional data

Nbr of points	1265
Blocs (script, sub sequence)	87
Time per points (electrical) (s)	1m15s
Data (Gb)	58

*this test campaign is applied on the RedHat project for the RedHat electrical machine

Initial results

At this point

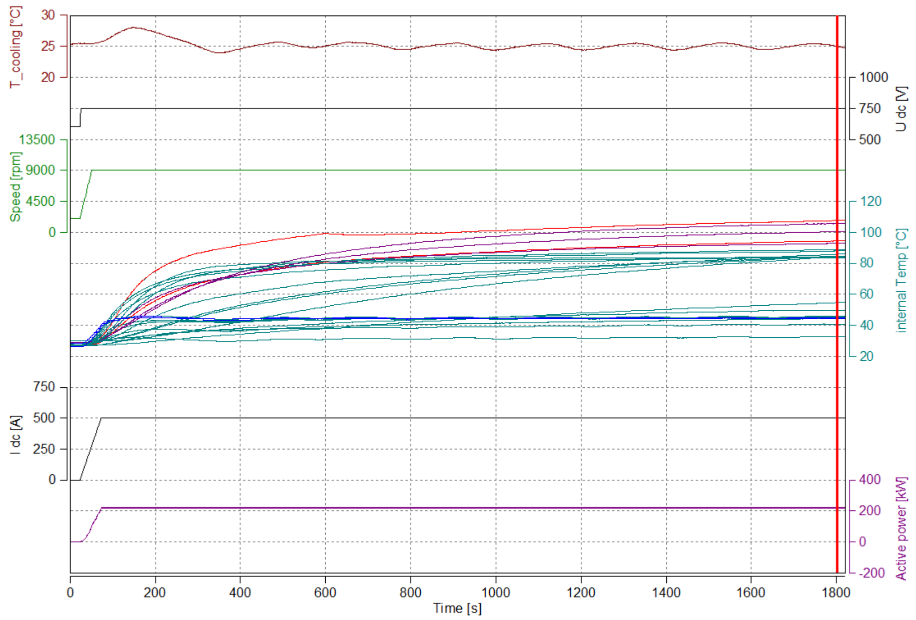
Highlighting the current derating
Reach the actual max power : 224 kW DC
Reach the the maximum Fsw, without thermal risks

Any T° < 120 °C

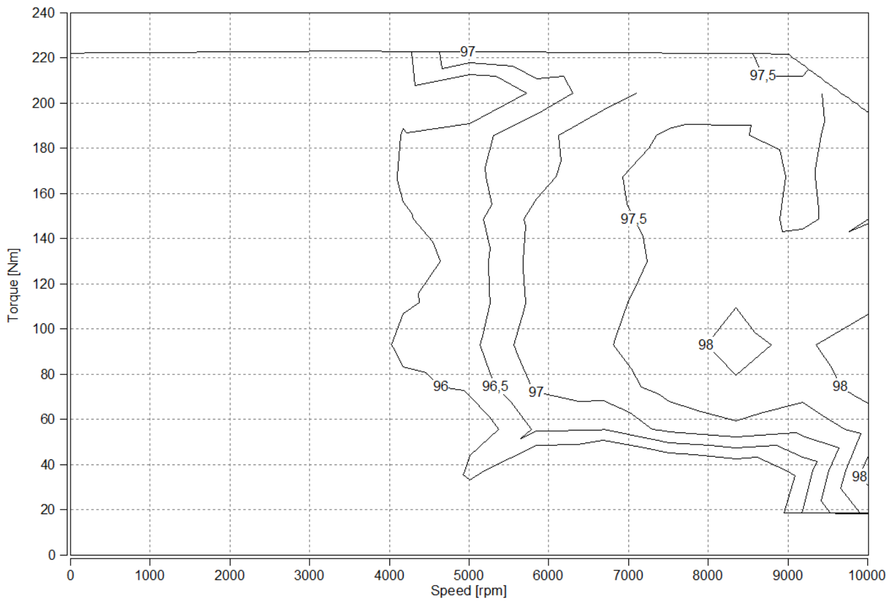
$$SVM = \frac{\sqrt{2}*Vrms}{Vdc} < 0,57$$

For example :

- 750 Vdc
- 531 Apk
- 30 kHz
- Tcooling = 25°C



Efficiency map :



Need more data !

a full Fsw scan

Test are in standby

Sw limitation, → Will be unlocked
Testbed availability

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Conclusion

Discussion & prospect

Results synthesis

Inverter laboratory Characterization :
- Characterization of Losses / Fsw
- Characterization of Power Module T+/ Fsw
- Characterization of Gate resistor T° / Fsw
- Thermal analysis

Power HIL testbench characterization :
- Efficiency
- Continus power (thermal)
- Inverter maximal rating (Fsw, Irms, …)
- Functional Control tests

Current limitations

Software limitation
Max phase current

Future perspectives

Complete de test Campaign (up to max Power/ Fsw)
Terminate de 4D mapping and identify the MTPA
Advanced control validation
EMC tests (impedance emulation)
Developing partnership and testing new ideas…

Impact on Power Electronics

A step-forward for more efficiency,
a better Fsw / P
Communication to the EP community

THANK YOU

For your attention

Now it's
Q&A
time

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virtual tour

Rue Christophe Colomb, Parc de la Porte Nord,
62700 BRUAY LA BUISSIERE - FRANCE

THE END

Bonus

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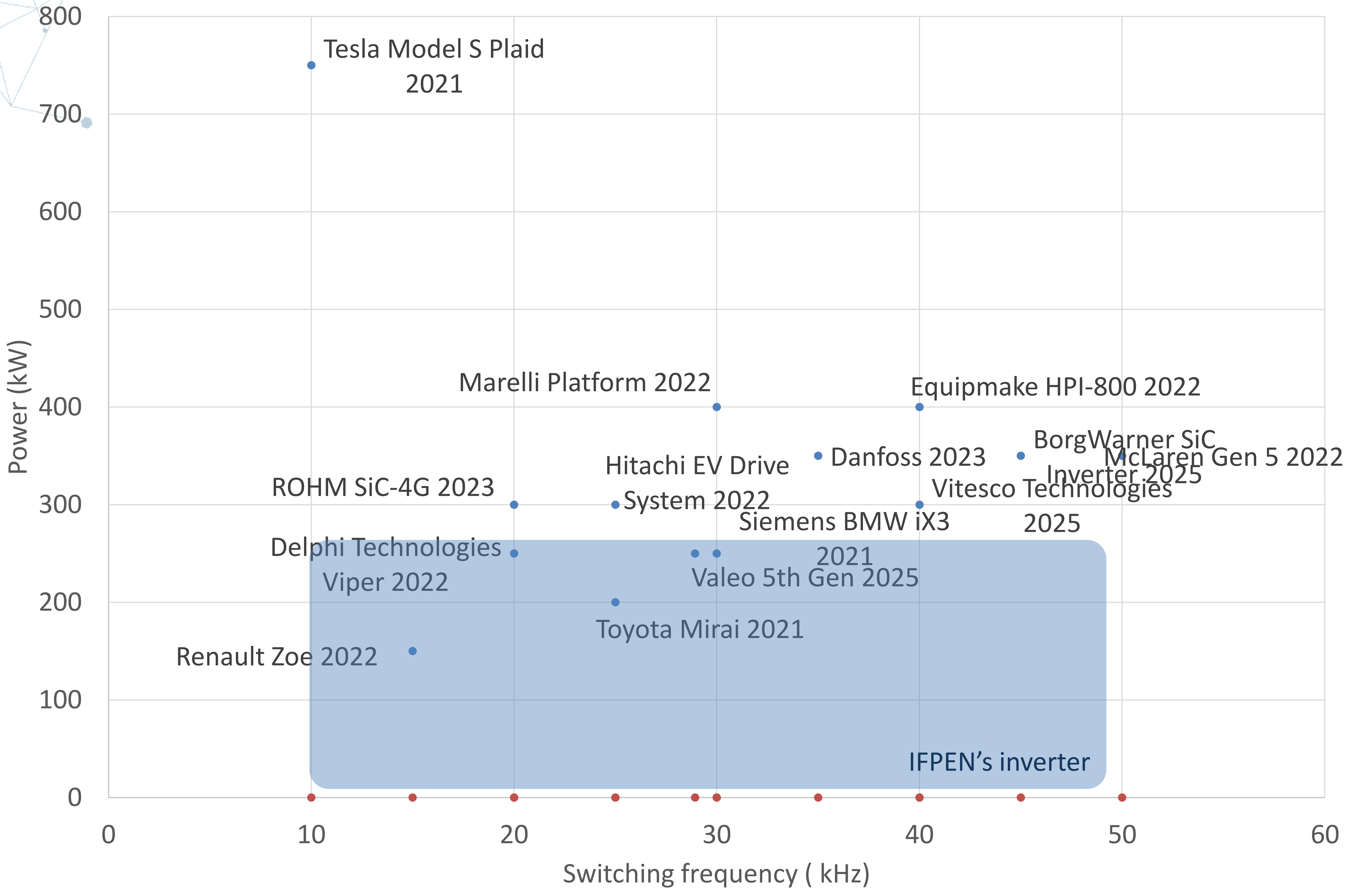
• Comparison with Existing Products



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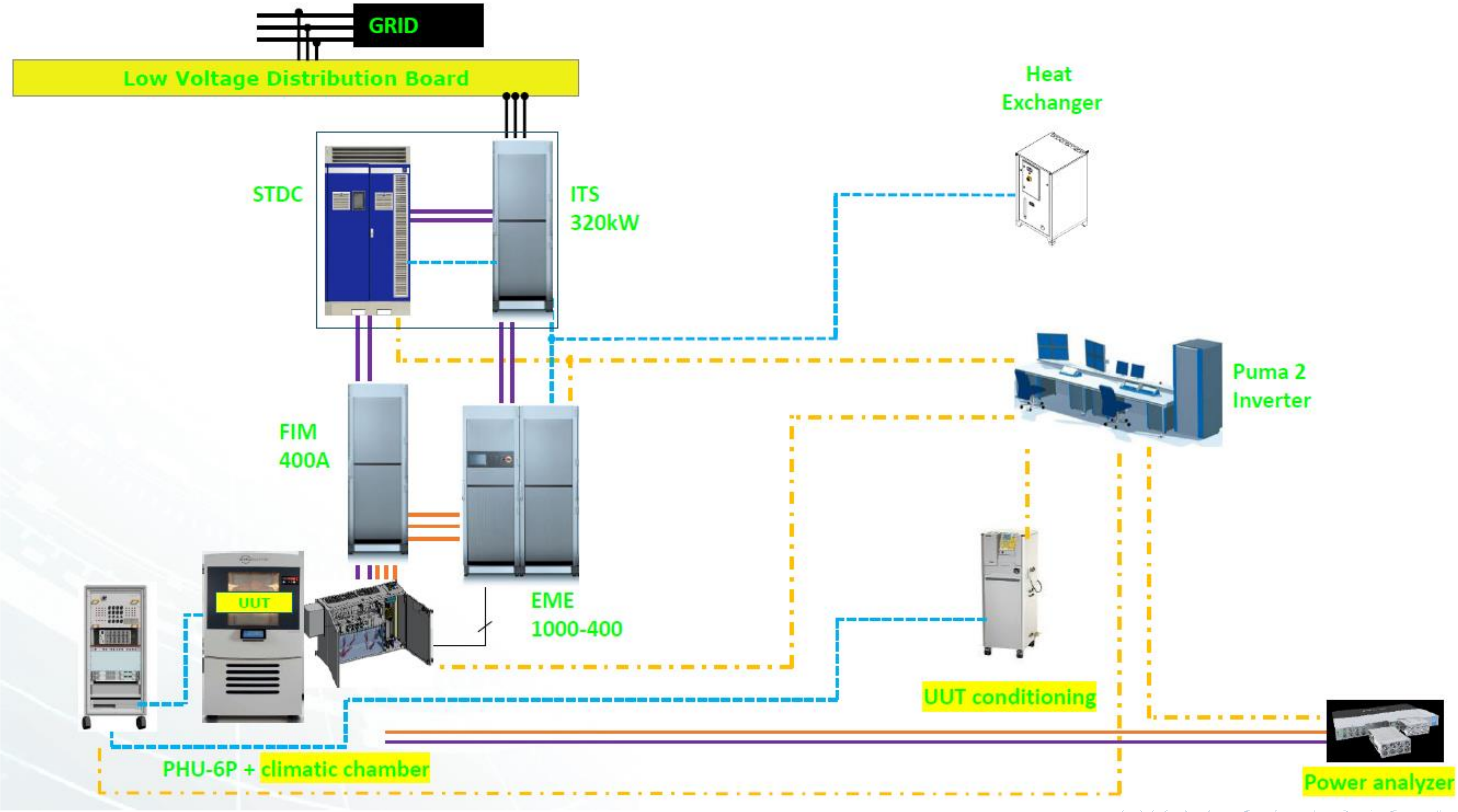
- https://www.grandviewresearch.com/industry-analysis/electric-mobility-market

Power HIL bench architecture



Power HIL bench Loops

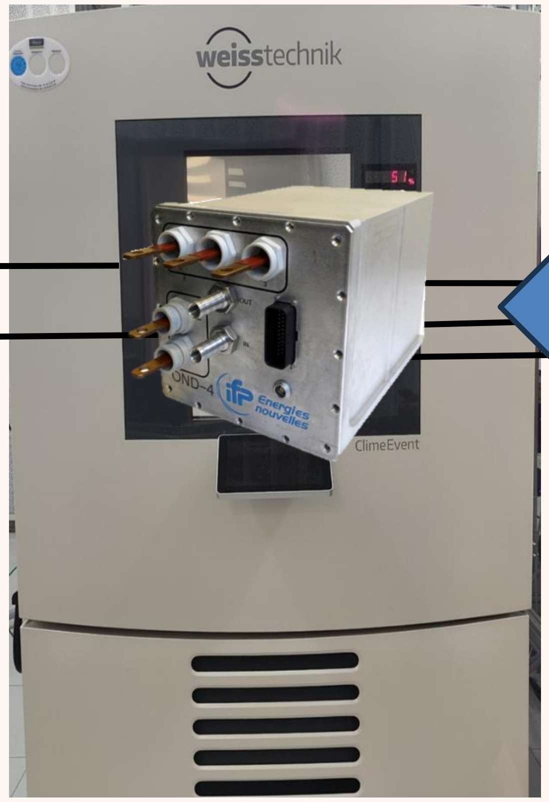
DC bus emulation

E-STORAGE

P_{max} = 320 kW
U_{max} = 1000 V
I_{max} = 800 A

DC

Temperature & humidity



Current : approximative 1ms (exécution time up to Fsw = 30 kHz)
speed : 100ms (execution time = 1 ms)

AC3

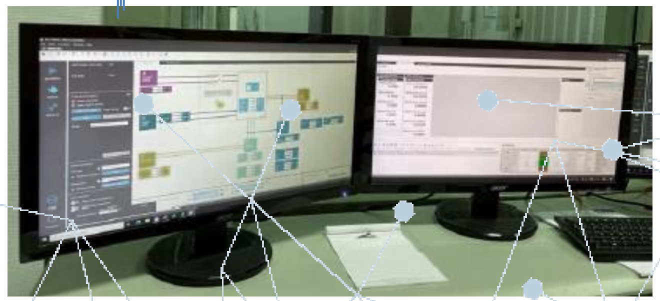
Electrical machine emulation

EME

3 phases
P_{max} = 320 kVA (AC or DC)
$U_{ph\text{-}ph}$ = 735 V
$I_{ph\text{-}max}$ = 400 Arms

Current 320 ns ?

CAN
Ethercat
TCP / IP



AVL PUMA II
(PUMA INVERTER)

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