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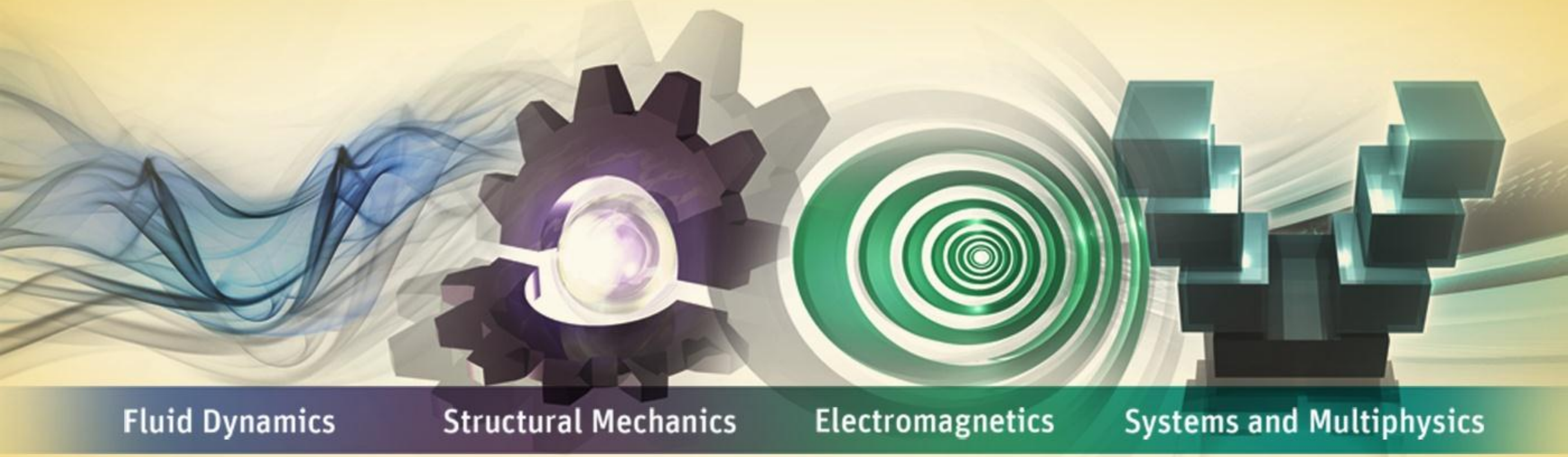
High Power Electronics Design



Zed (Zhangjun) Tang

ANSYS, Inc

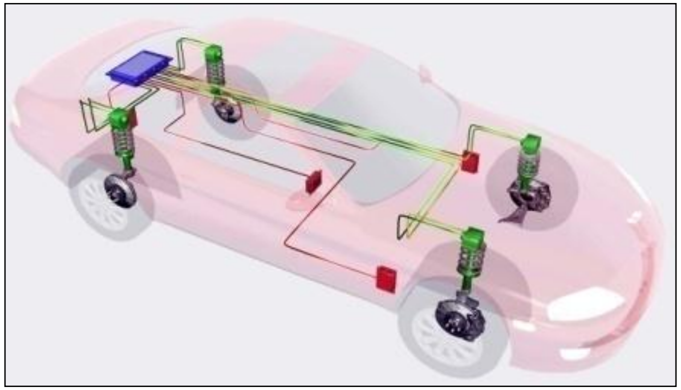
June 3, 2014

Outline

- Part I: EMI/EMC
- Part II: Multiphysics – Thermal/Structural

Part I: EMI/EMC

- EMI/EMC
  – Magnetic Field
  – Electric Field
  – Conducted Fields
  – Radiated Fields
  – Testing and solutions
  – Simulation is solving EMI/EMC problems both quantitatively and qualitatively



"Electronics is outpacing the basic construction of these boards . . . we're going to have to change how we do things."

- Paul Huray, Ph.D.

Professor of Electrical Engineering, University of South Carolina

Agenda

High Power Electronics/Motor Drives – EMI/EMC

* Power Device (IGBT, MOSFET, Power Diode) model extraction

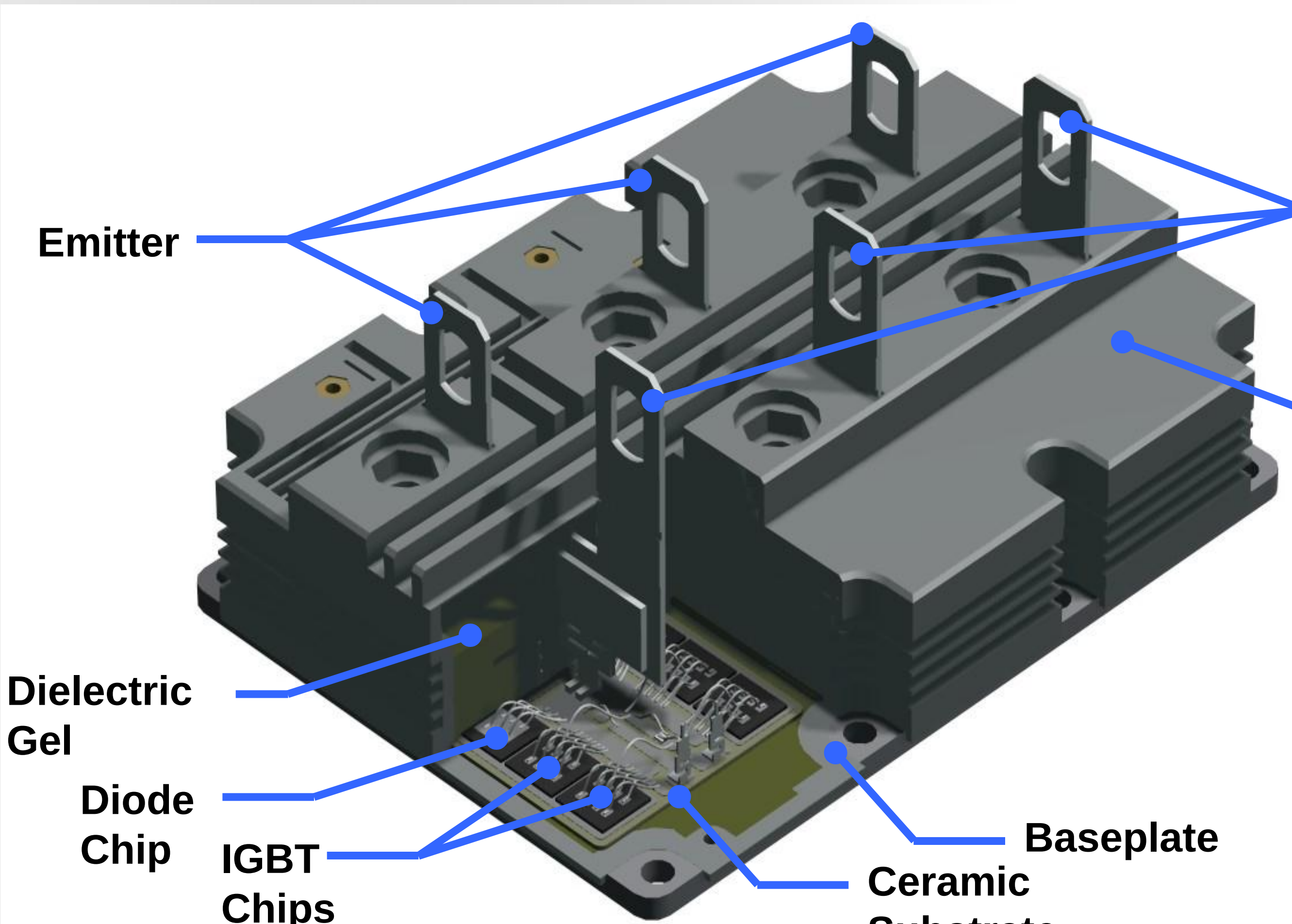
* Busbar/Cable Parasitics extraction (frequency dependent LCR model)

* System Integration – PWM frequency/control algorithm

* Conducted/Radiated EMI/EMC

Introduction

6.5kV IGBT Module Characteristics



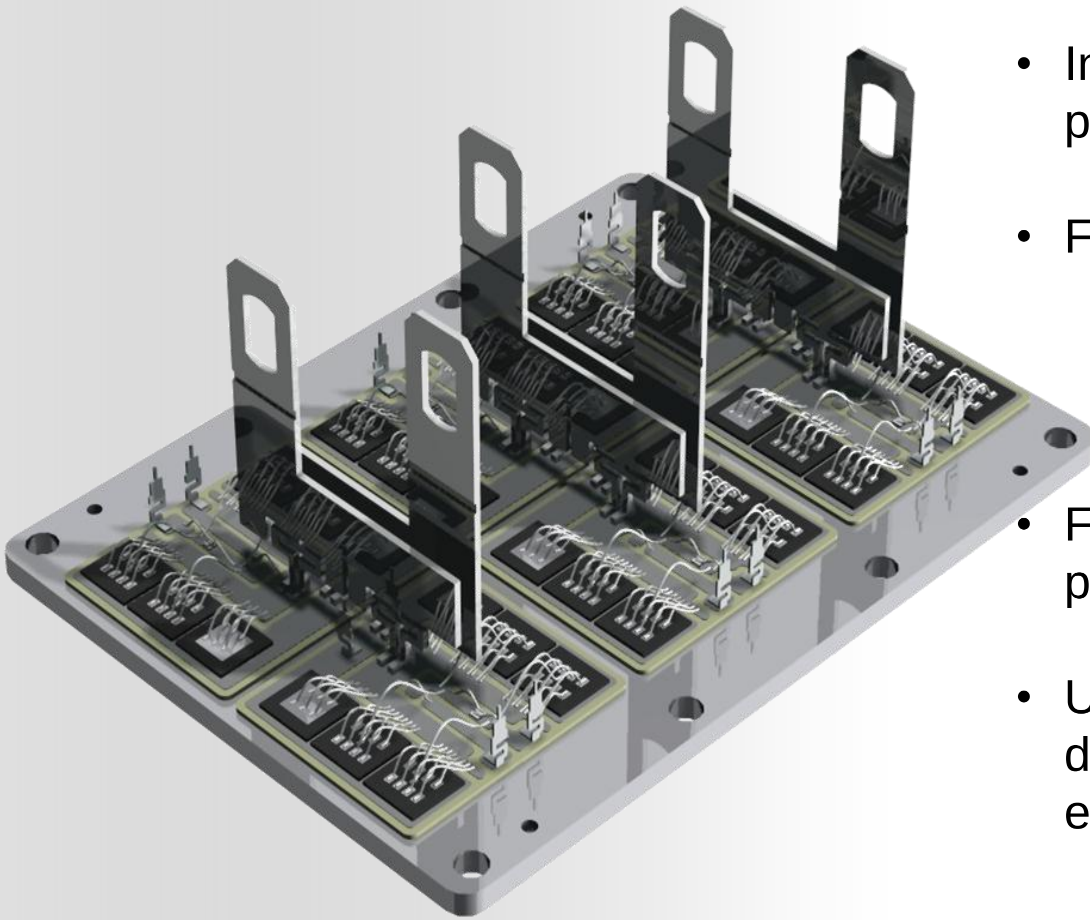
6.5kV-600A Module

24 IGBT and

12 Diode Chips

Introduction

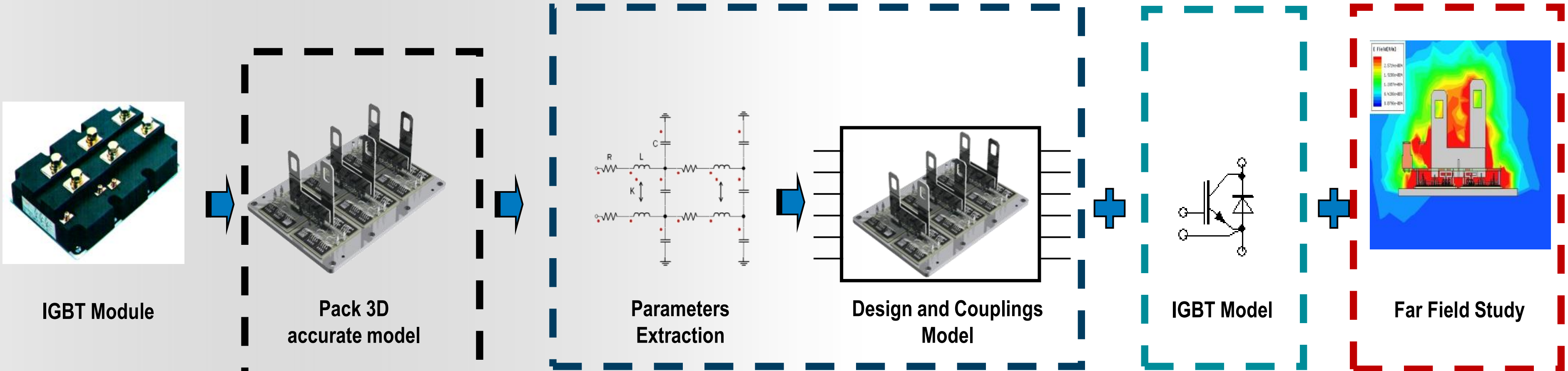
6.5kV IGBT Module Analysis

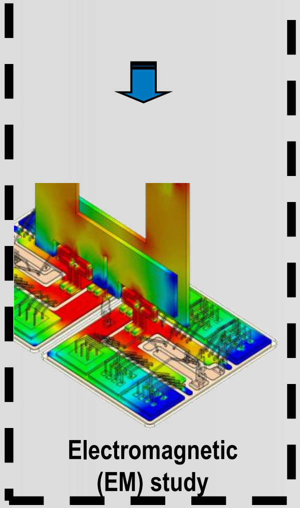


- Include package in IGBT performance
- Find DC current distribution
- Find switching currents for power dissipation
- Use power dissipation to determine environmental electromagnetic fields

Introduction

Model design developed at Alstom/Pearl





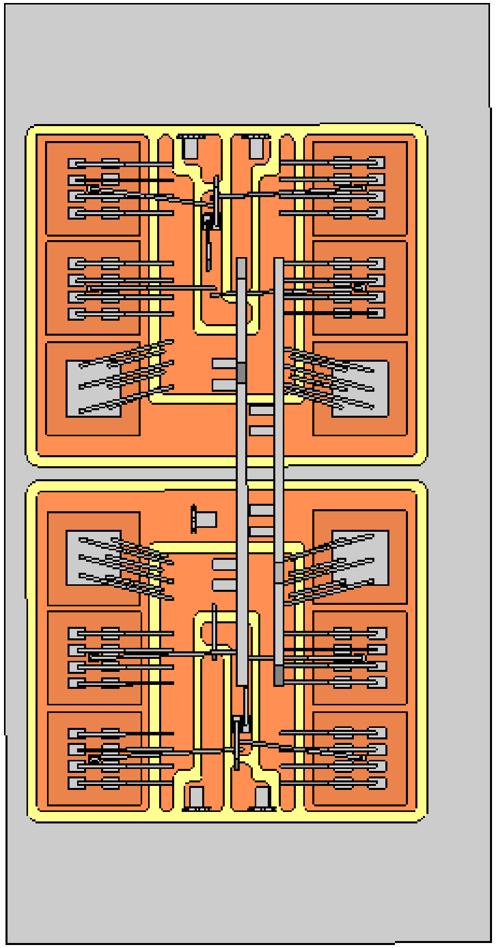
- **Tridimensional IGBT pack model and EM study**
- **Parasitic model extraction**
- **IGBT circuit model**
- **Far Field Study for Electric Field EM**

ElectroMagnetic Study

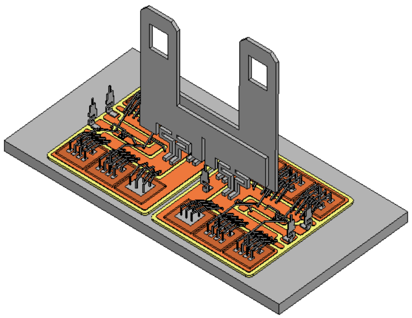
Module layout verification

The module contains 8 IGBTs in parallel: does each IGBT receive the same amount of current?

- **If the current flows un-evenly, this will cause mechanical stress and reliability issues.**
- **Electromagnetic simulation is required. We use Maxwell3D.**



ElectroMagnetic Study

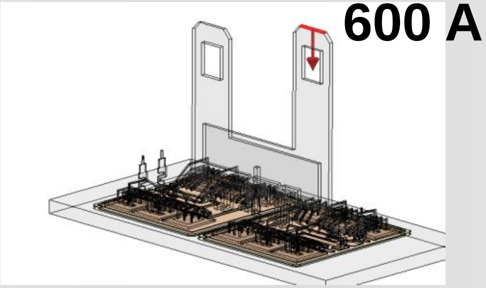


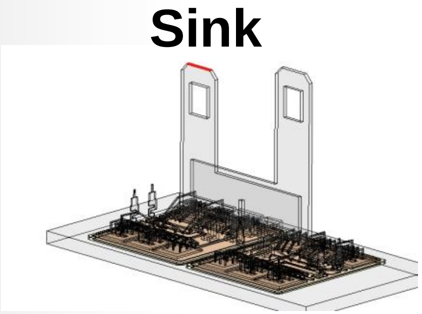
The layout in imported from the CAD tool

The DC solver is used

The input current (600 A) is defined

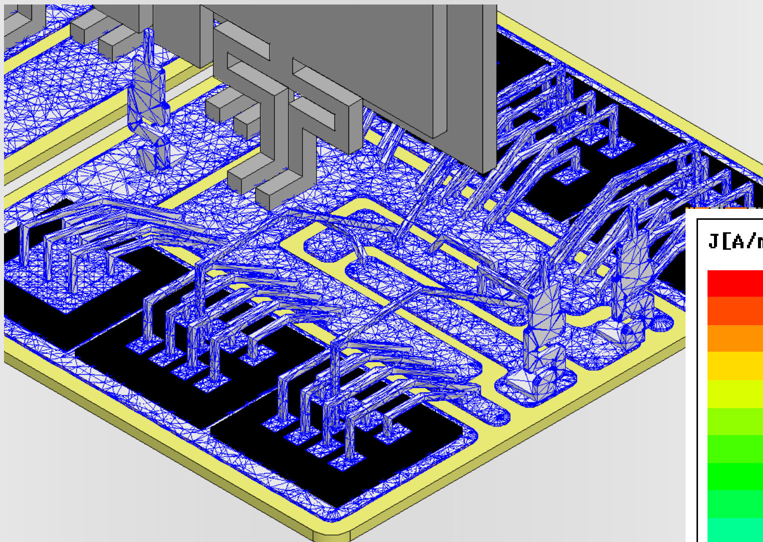
The sink (return current path) is defined





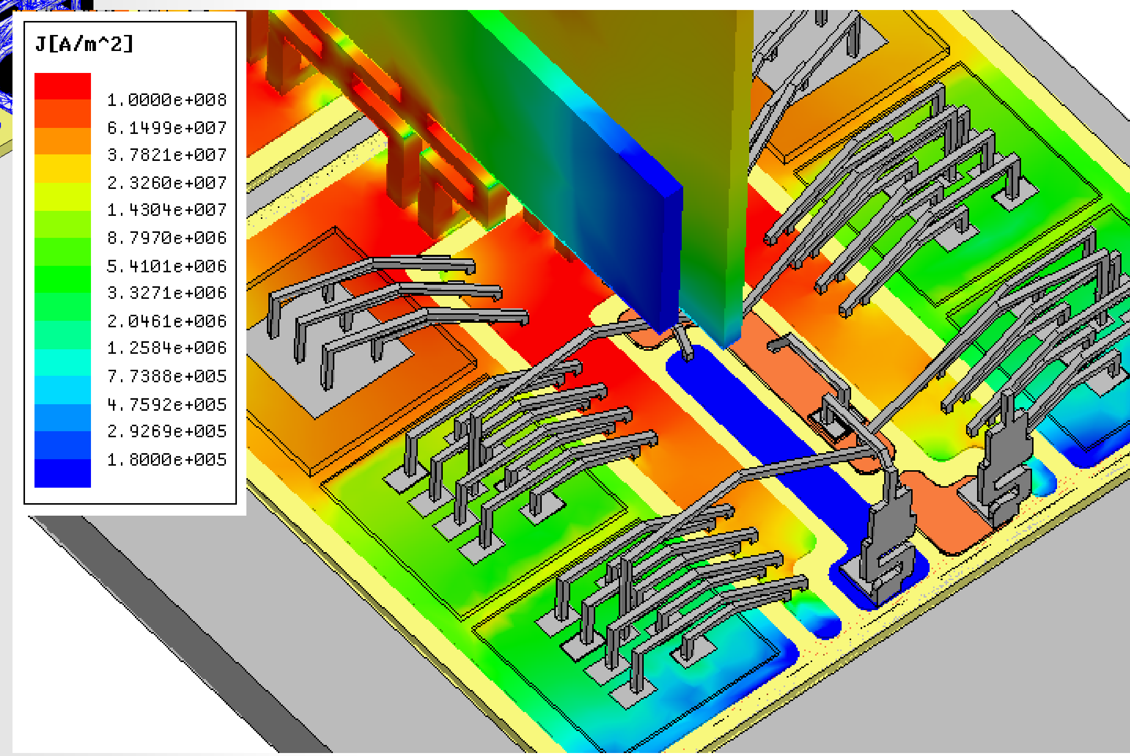
Outputs: conduction path and current distribution

ElectroMagnetic Study



The structure is meshed using automatic and adaptive meshing

Current Distribution
IGBTs on, Diodes off



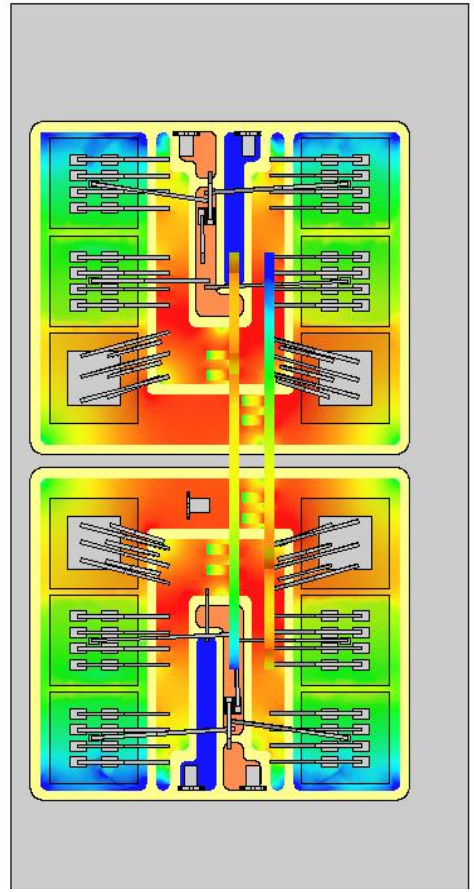
  June 3, 2014

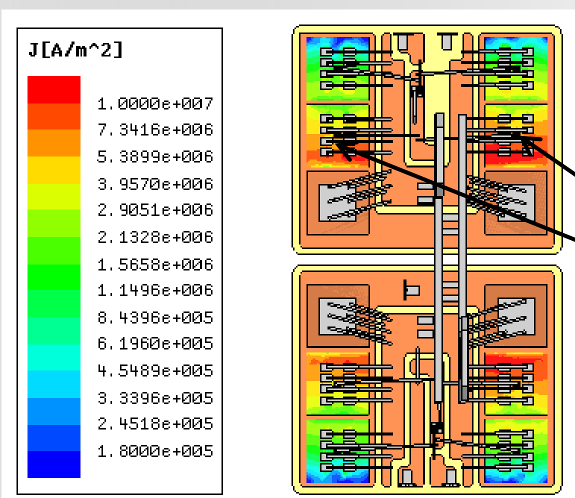
ElectroMagnetic Study

The end IGBTs see less current than the center ones.

This can cause reliability issues as the center IGBTs will be overloaded

An optimization of the copper tracks can be made in order to equalize the currents.

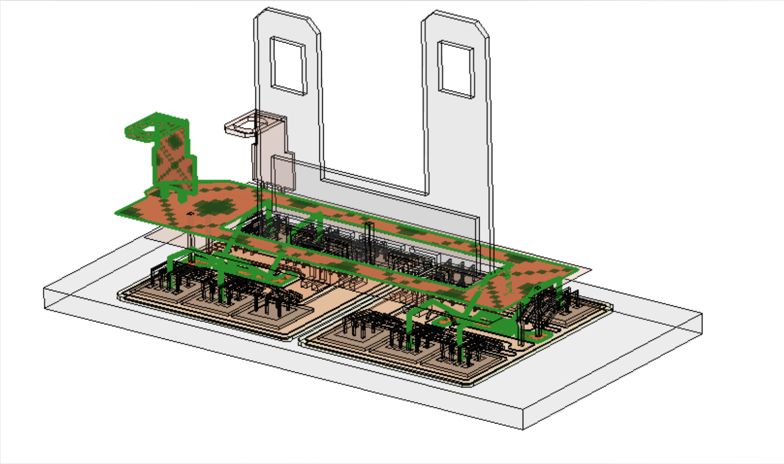


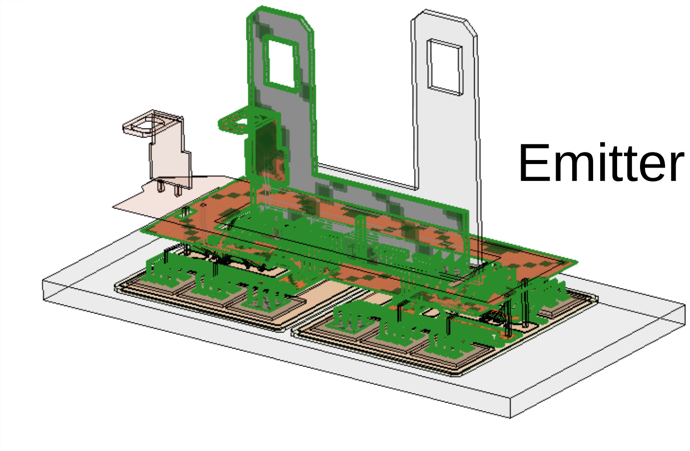


Igbt1a and Igbt4a have the highest quantity of current

Parasitics Extraction

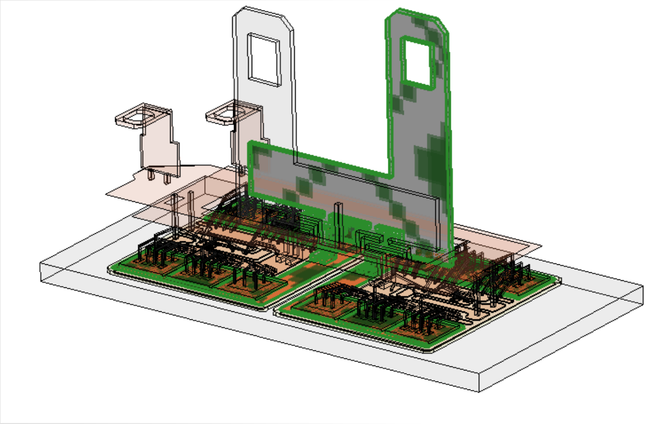
Extracting parameters is straightforward as the nets are automatically assigned.





Emitter net

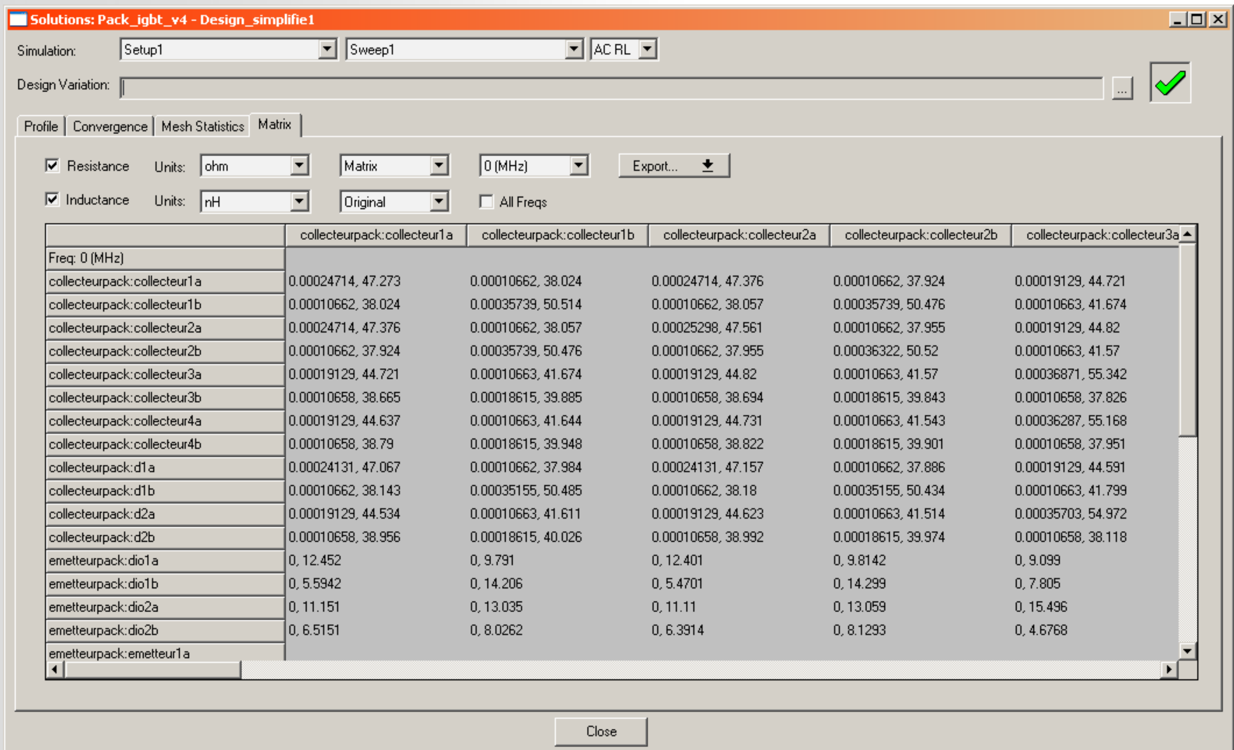
Gate net



Collector net

Parasitics Extraction

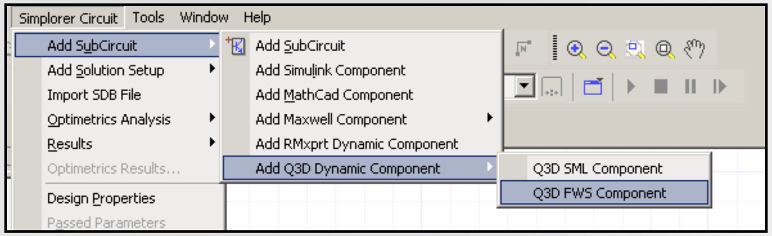
- The simulation outputs consist of the RLC matrices for different frequencies

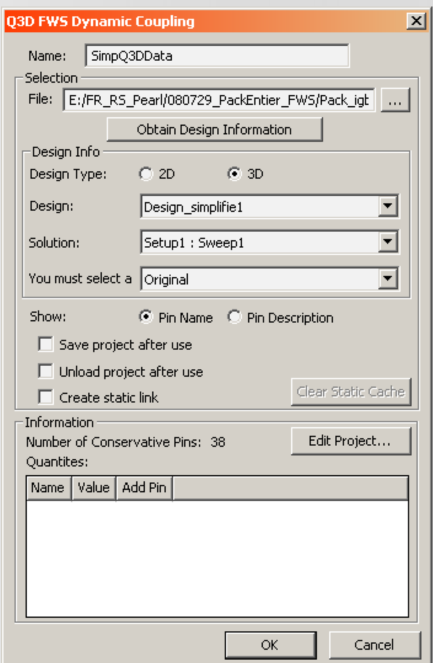


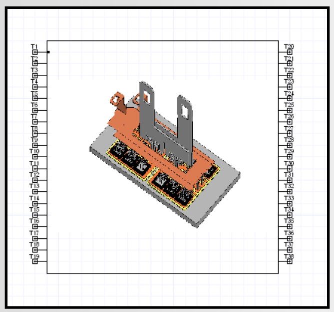
	collecteurpack:collecteur1a	collecteurpack:collecteur1b	collecteurpack:collecteur2a	collecteurpack:collecteur2b	collecteurpack:collecteur3a
Freq: 0 (MHz)					
collecteurpack:collecteur1a	0.00024714, 47.273	0.00010662, 38.024	0.00024714, 47.376	0.00010662, 37.924	0.00019129, 44.721
collecteurpack:collecteur1b	0.00010662, 38.024	0.00035739, 50.514	0.00010662, 38.057	0.00035739, 50.476	0.00010663, 41.674
collecteurpack:collecteur2a	0.00024714, 47.376	0.00010662, 38.057	0.00025298, 47.561	0.00010662, 37.955	0.00019129, 44.82
collecteurpack:collecteur2b	0.00010662, 37.924	0.00035739, 50.476	0.00010662, 37.955	0.00036322, 50.52	0.00010663, 41.57
collecteurpack:collecteur3a	0.00019129, 44.721	0.00010663, 41.674	0.00019129, 44.82	0.00010663, 41.57	0.00036871, 55.342
collecteurpack:collecteur3b	0.00010658, 38.665	0.00018615, 39.885	0.00010658, 38.694	0.00018615, 39.843	0.00010658, 37.826
collecteurpack:collecteur4a	0.00019129, 44.637	0.00010663, 41.644	0.00019129, 44.731	0.00010663, 41.543	0.00036287, 55.168
collecteurpack:collecteur4b	0.00010658, 38.79	0.00018615, 39.948	0.00010658, 38.822	0.00018615, 39.901	0.00010658, 37.951
collecteurpack:d1a	0.00024131, 47.067	0.00010662, 37.984	0.00024131, 47.157	0.00010662, 37.886	0.00019129, 44.591
collecteurpack:d1b	0.00010662, 38.143	0.00035155, 50.485	0.00010662, 38.18	0.00035155, 50.434	0.00010663, 41.799
collecteurpack:d2a	0.00019129, 44.534	0.00010663, 41.611	0.00019129, 44.623	0.00010663, 41.514	0.00035703, 54.972
collecteurpack:d2b	0.00010658, 38.956	0.00018615, 40.026	0.00010658, 38.992	0.00018615, 39.974	0.00010658, 38.118
emetteurpack:dio1a	0, 12.452	0, 9.791	0, 12.401	0, 9.8142	0, 9.099
emetteurpack:dio1b	0, 5.5942	0, 14.206	0, 5.4701	0, 14.299	0, 7.805
emetteurpack:dio2a	0, 11.151	0, 13.035	0, 11.11	0, 13.059	0, 15.496
emetteurpack:dio2b	0, 6.5151	0, 8.0262	0, 6.3914	0, 8.1293	0, 4.6768
emetteurpack:emetteur1a					

System Integration

- How do we import the results from Q3D?: ***Q3D dynamic link***

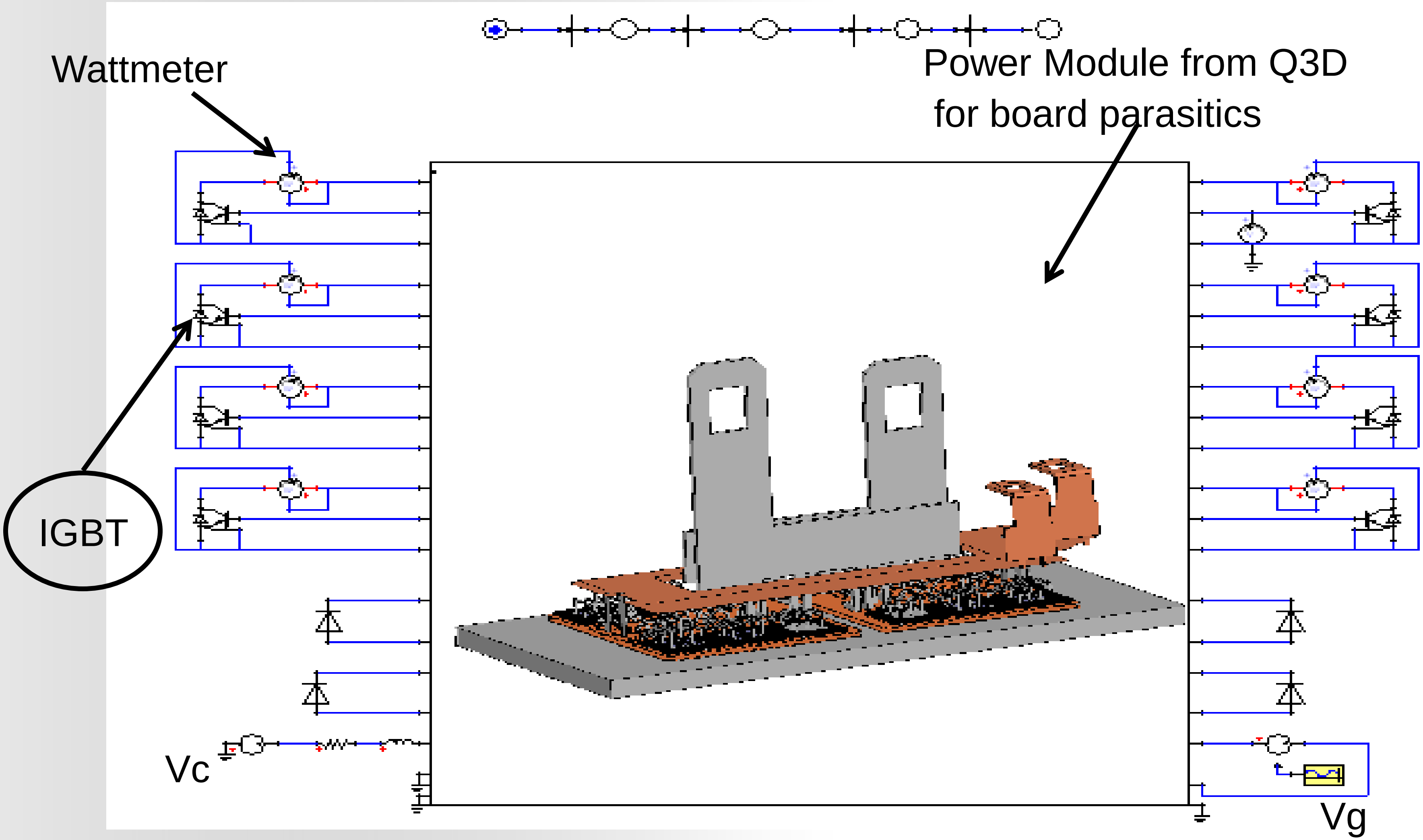






- 2 Types of links: Single Frequency or Frequency dependent
- No need to manually import output file
- Simplorer incorporates directly the Q3D project
- If some results are not available, Simplorer dynamically launches Q3D
- Parameters and variables can be passed between S8 and Q3D

System Simulation



IGBT Characterization

Technische Information / Technical Information

eupec

IGBT-Module
IGBT-Modules

FZ 600 R 65 KF1

Höchstzulässige Werte / Maximum rated values

Elektrische Eigenschaften / Electrical properties

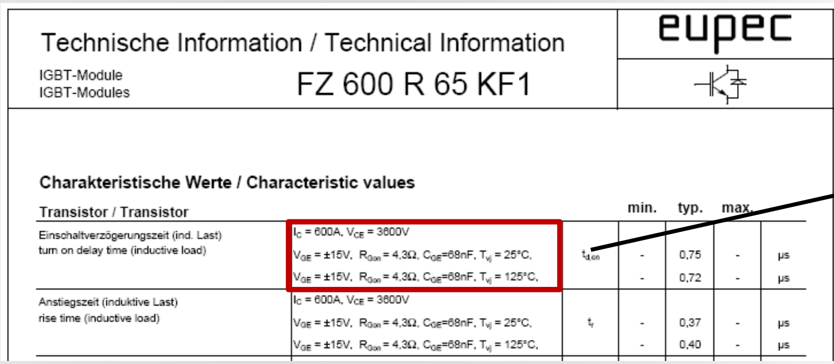
Kollektor-Emitter-Sperrspannung collector-emitter voltage	T_{vj}=125°C T_{vj}=25°C T_{vj}=-40°C	V_{CES}	6500 6300 5800	V
Kollektor-Dauergleichstrom DC-collector current	T_C = 80 °C T_C = 25 °C	$I_{C,nom}$ I_C	600 1200	A A
Periodischer Kollektor Spitzenstrom repetitive peak collector current	t_P = 1 ms, T_C = 80°C	I_{CRM}	1200	A
Gesamt-Verlustleistung total power dissipation	T_C=25°C, Transistor	P_{tot}	11,4	kW
Gate-Emitter-Spitzenspannung gate-emitter peak voltage		V_{GES}	+/- 20V	V
Dauergleichstrom DC forward current		I_F	600	A
Periodischer Spitzenstrom repetitive peak forw. current	t_P = 1 ms	I_{FRM}	1200	A
Grenzlastintegral der Diode I^2t - value, Diode	V_R = 0V, t_P = 10ms, T_{vj} = 125°C	I^2t	165	k A^2s
Isolations-Prüfspannung insulation test voltage	RMS, f = 50 Hz, t = 1 min.	V_{ISOL}	10,2	kV
Teilentladungs Aussetzspannung partial discharge extinction voltage	RMS, f = 50 Hz, Q_{PD} typ. 10pC (acc. To IEC 1287)	V_{ISOL}	5,1	kV

Charakteristische Werte / Characteristic values

Transistor / Transistor			min.	typ.	max.	
Kollektor-Emitter Sättigungsspannung collector-emitter saturation voltage	I_C = 600A, V_{GE} = 15V, T_{vj} = 25°C I_C = 600A, V_{GE} = 15V, T_{vj} = 125°C	$V_{CE\ sat}$	- -	4,3 5,3	4,9 5,9	V V
Gate-Schwellenspannung gate threshold voltage	I_C = 100mA, V_{CE} = V_{GE}, T_{vj} = 25°C	$V_{GE(th)}$	6,4	7,0	8,1	V
Gateladung gate charge	V_{GE} = -15V ... +15V	Q_G	-	8,4	-	µC
Eingangskapazität input capacitance	f = 1MHz, T_{vj} = 25°C, V_{CE} = 25V, V_{GE} = 0V	C_{ies}	-	84	-	nF
Kollektor-Emitter Reststrom collector-emitter cut-off current	V_{CE} = 6300V, V_{GE} = 0V, T_{vj} = 25°C V_{CE} = 6500V, V_{GE} = 0V, T_{vj} = 125°C	I_{CES}	-	0,6 60	-	mA mA
Gate-Emitter Reststrom gate-emitter leakage current	V_{CE} = 0V, V_{GE} = 20V, T_{vj} = 25°C	I_{GES}	-	-	400	nA

- Accurate models of the semiconductors are needed to achieve a good circuit simulation
- Simplorer offers a parameterization tool for IGBTs
- The user needs to import the data from the datasheet

IGBT Characterization



Technische Information / Technical Information

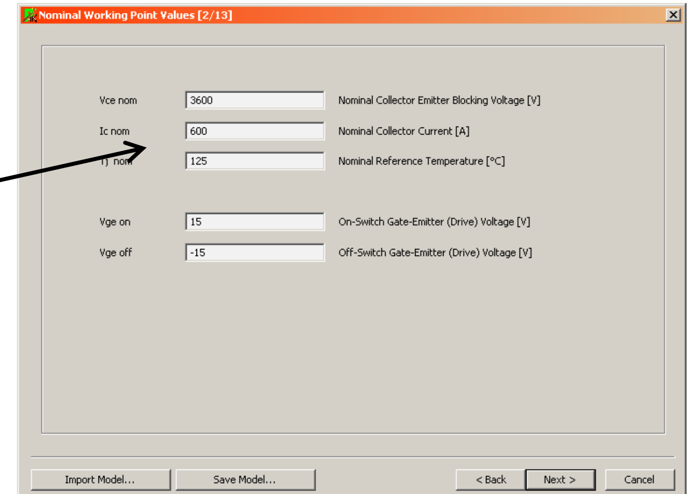
eupec

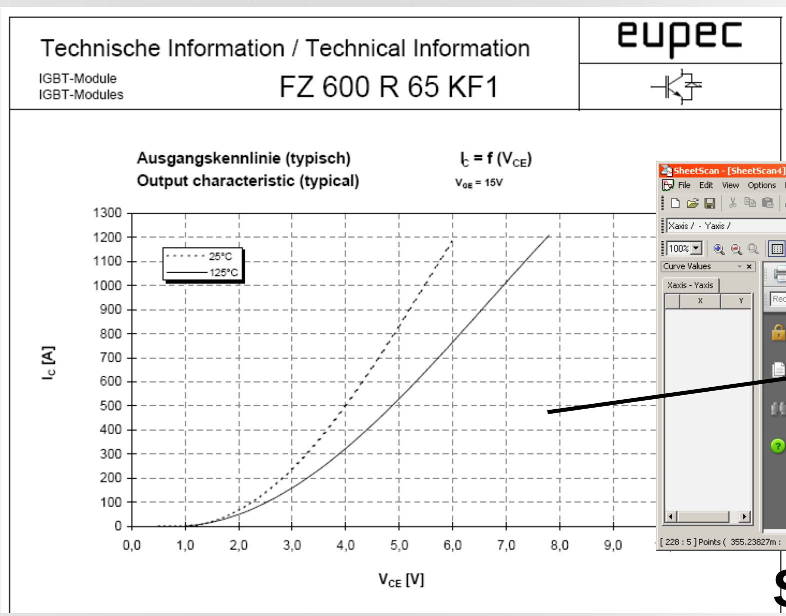
IGBT-Module
IGBT-Modules

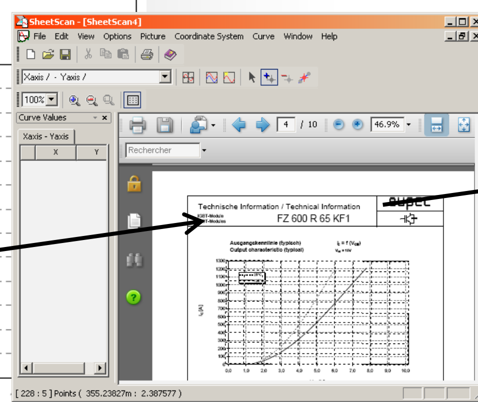
FZ 600 R 65 KF1

Charakteristische Werte / Characteristic values

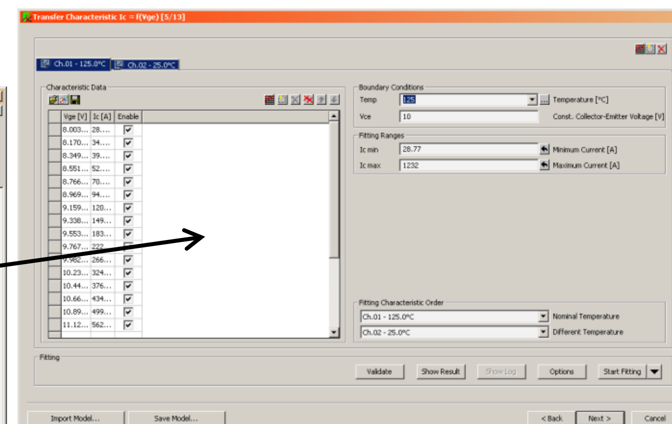
Transistor / Transistor			min.	typ.	max.	
Einschaltverzögerungszeit (ind. Last) turn on delay time (inductive load)	I_C = 600A, V_{CE} = 3600V					
	V_{GE} = ±15V, R_{Gon} = 4,3Ω, C_{GE}=68nF, T_{vj} = 25°C,	$t_{d,on}$	-	0,75	-	µs
	V_{GE} = ±15V, R_{Gon} = 4,3Ω, C_{GE}=68nF, T_{vj} = 125°C,		-	0,72	-	µs
Anstiegszeit (induktive Last) rise time (inductive load)	I_C = 600A, V_{CE} = 3600V					
	V_{GE} = ±15V, R_{Gon} = 4,3Ω, C_{GE}=68nF, T_{vj} = 25°C,	t_r	-	0,37	-	µs
	V_{GE} = ±15V, R_{Gon} = 4,3Ω, C_{GE}=68nF, T_{vj} = 125°C,		-	0,40	-	µs







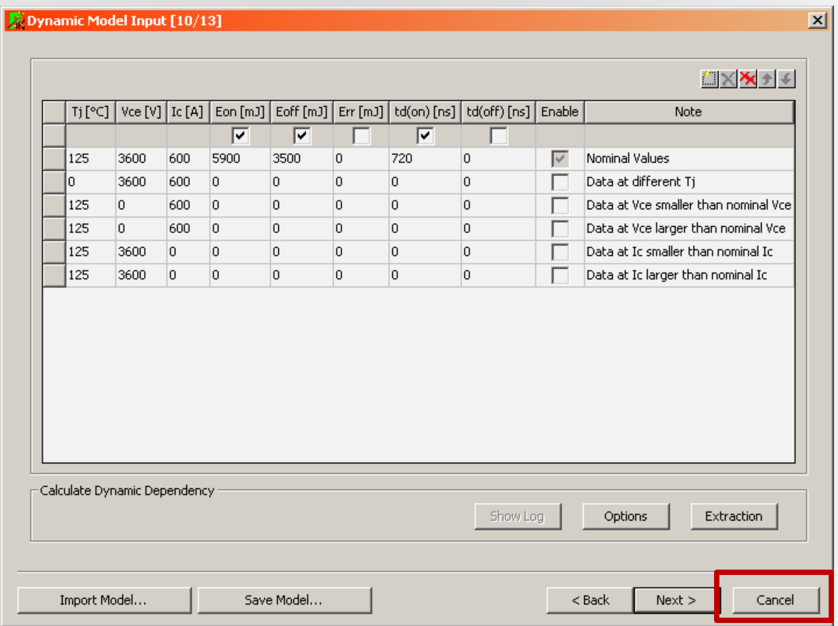
SheetScan



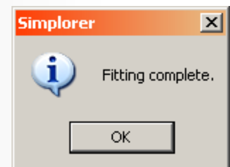
IGBT Characterization

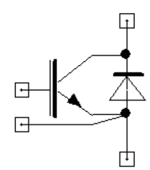
Once all the curves and data are entered, start extraction

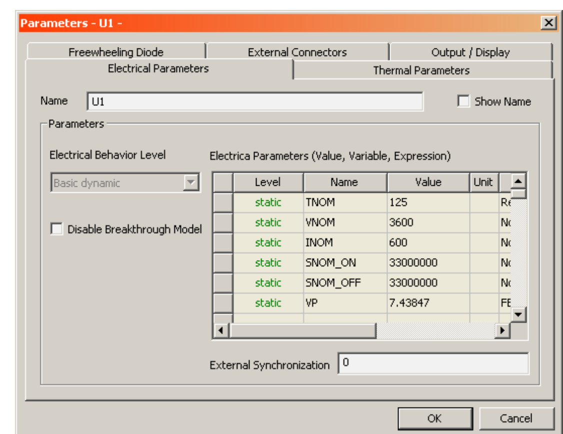
The tool fits the data to the internal Simplorer model using Genetic Algorithm



Characterization tool



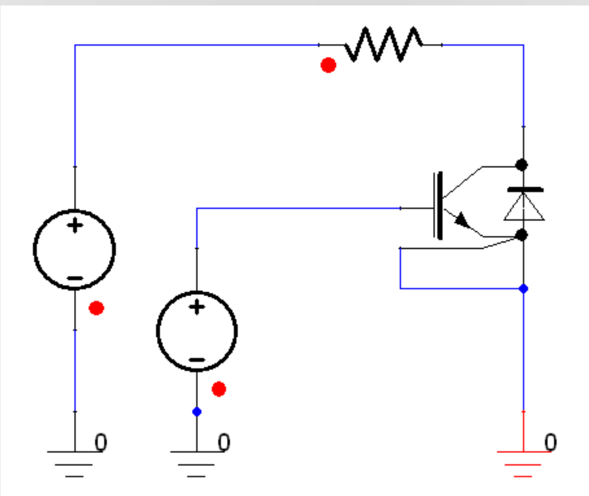




Component dialog

IGBT Characterization

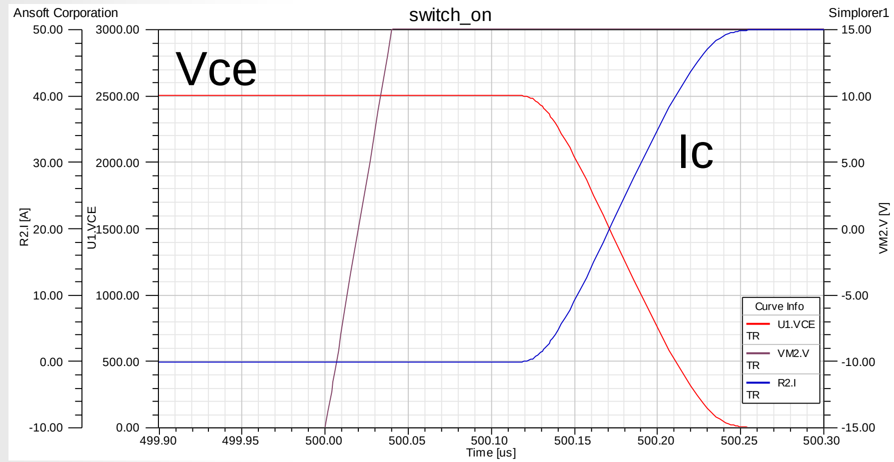
Test Circuit



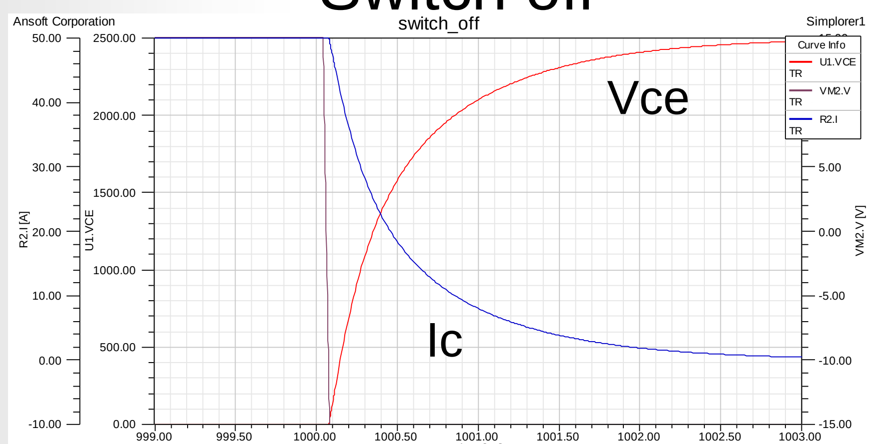
rise time= 40 µs

fall time = 50 µs

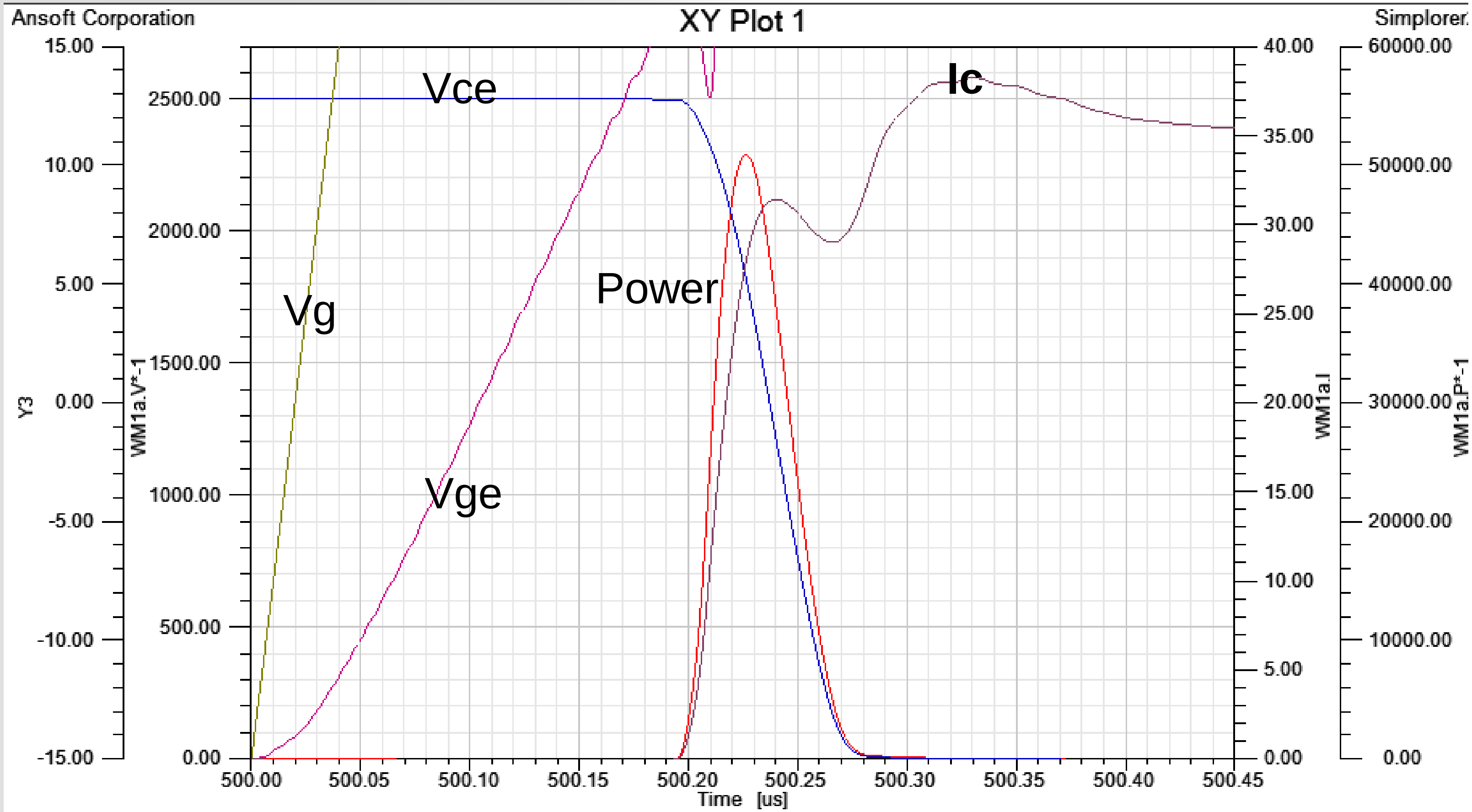
Switch on



Switch off

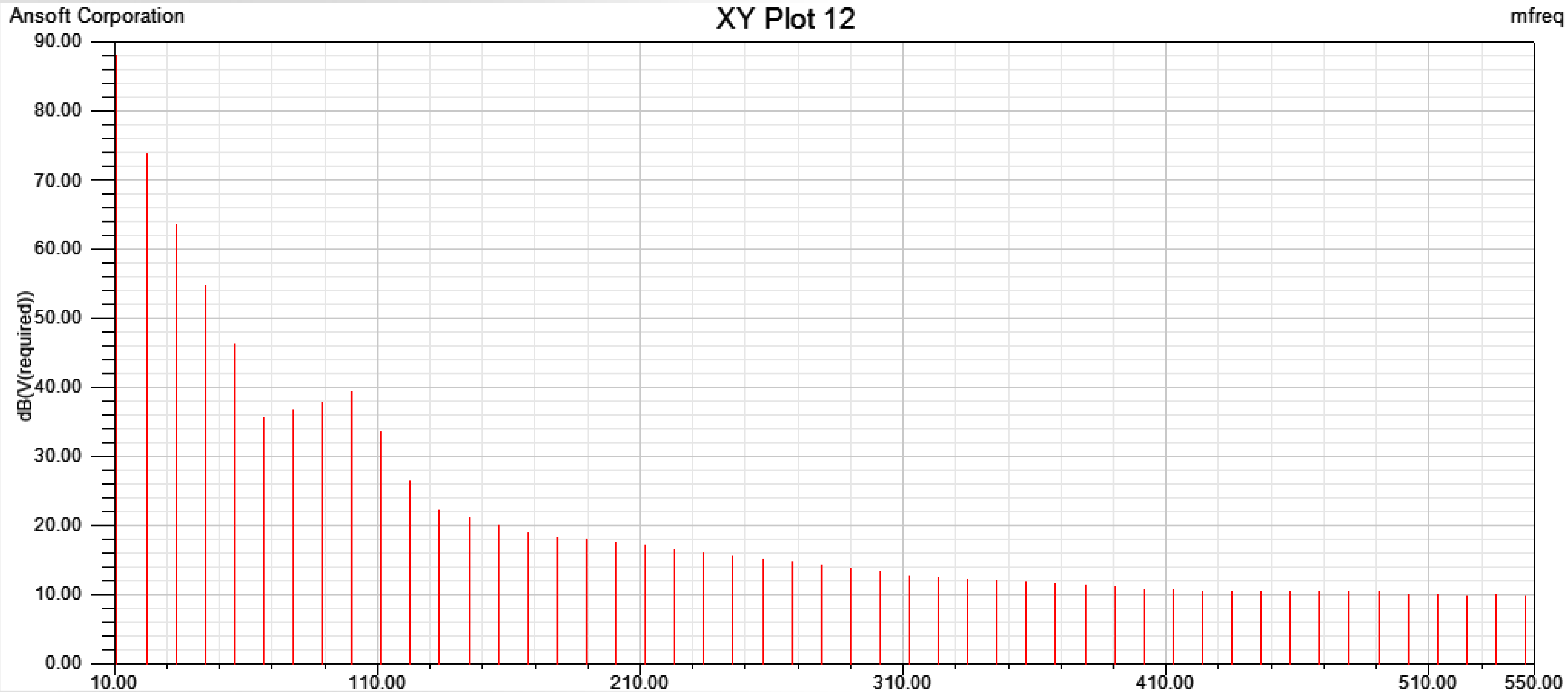


System Simulation



The power pulse duration is much smaller than the rise/fall time of Ic and Vce

System Simulation



FTT of the power through Igbt1a

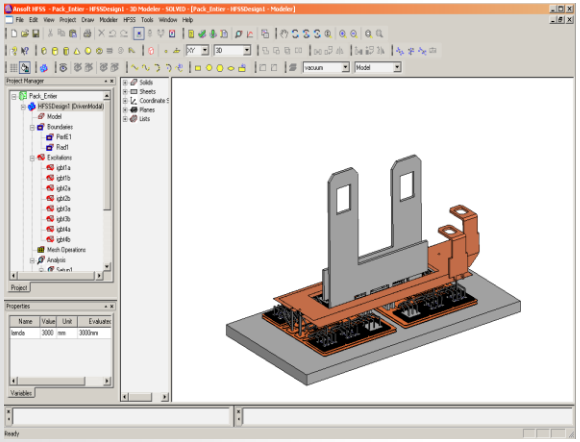
Most of the power level is below 110 MHz

Emitted Fields

- There is very high power going through the IGBTs (almost 60 000 W in this study) during a very short period of time (60 ns). This switching can cause EMI issues in the inverter, but also in the surrounding equipment

- To be answered using the finite element method in HFSS:

  - Will the module radiate?
  - Are the field levels surrounding the module within mandated levels?



Emitted Fields

Frequency range	Electric field strength, E (V/m)	Magnetic field strength, H (A/m)	Magnetic flux density, B (µT)	Equivalent plane wave power density, S_{eq} (W/m²)	Contact current, I_C(mA)	Limb induced current, I_L(mA)
0 — 1Hz	—	$1{,}63 \times 10^5$	2×10^5	—	1,0	—
1 — 8 Hz	20 000	$1{,}63 \times 10^5/f^2$	$2 \times 10^5/f^2$	—	1,0	—
8 — 25 Hz	20 000	$2 \times 10^4/f$	$2{,}5 \times 10^4/f$	—	1,0	—
0,025 — 0,82kHz	500/f	20/f	25/f	—	1,0	—
0,82 — 2,5 kHz	610	24,4	30,7	—	1,0	—
2,5 — 65 kHz	610	24,4	30,7	—	0,4 f	—
65 — 100 kHz	610	1 600/f	2 000/f	—	0,4 f	—
0,1 — 1 MHz	610	1,6/f	2/f	—	40	—
1 — 10 MHz	610/f	1,6/f	2/f	—	40	—
10 — 110 MHz	61	0,16	0,2	10	40	100
110 — 400 MHz	61	0,16	0,2	10	—	—
400 — 2 000 MHz	$3f^{1/2}$	$0{,}008f^{1/2}$	$0{,}01f^{1/2}$	f/40	—	—
2 — 300 GHz	137	0,36	0,45	50	—	—

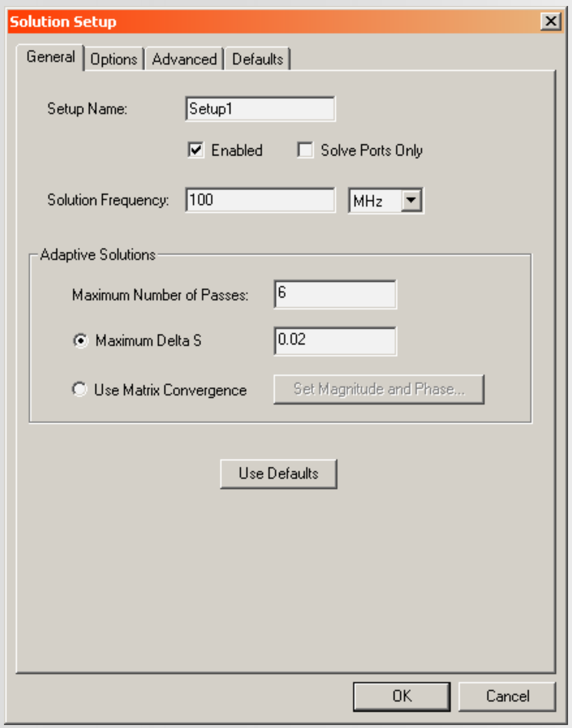
- Regulators impose maximum levels of electric fields close to electric equipment.
- In the 10-110 MHz range:

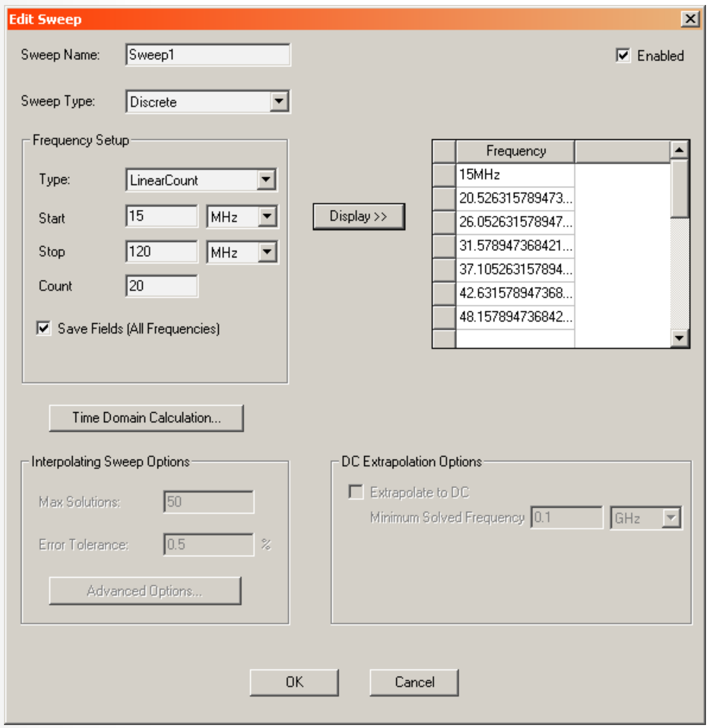
  Emax=61V/m

Exposure limits defined by European Community

Emitted Fields

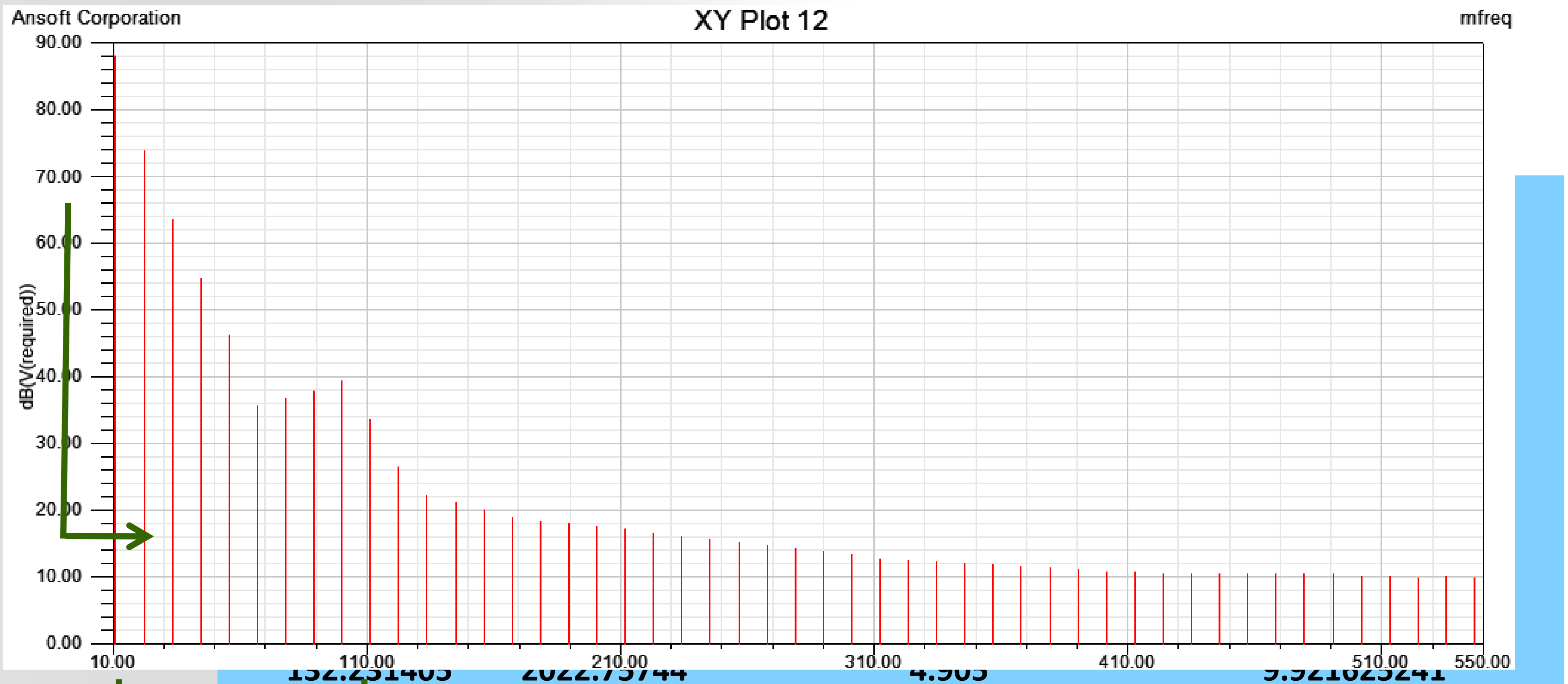
- The structure is discretized with adaptive meshing. The meshing frequency is 100 MHz
- The frequency sweep ranges from 15MHz to 120 MHz





Emitted Fields

For each frequency, the power amplitude is entered



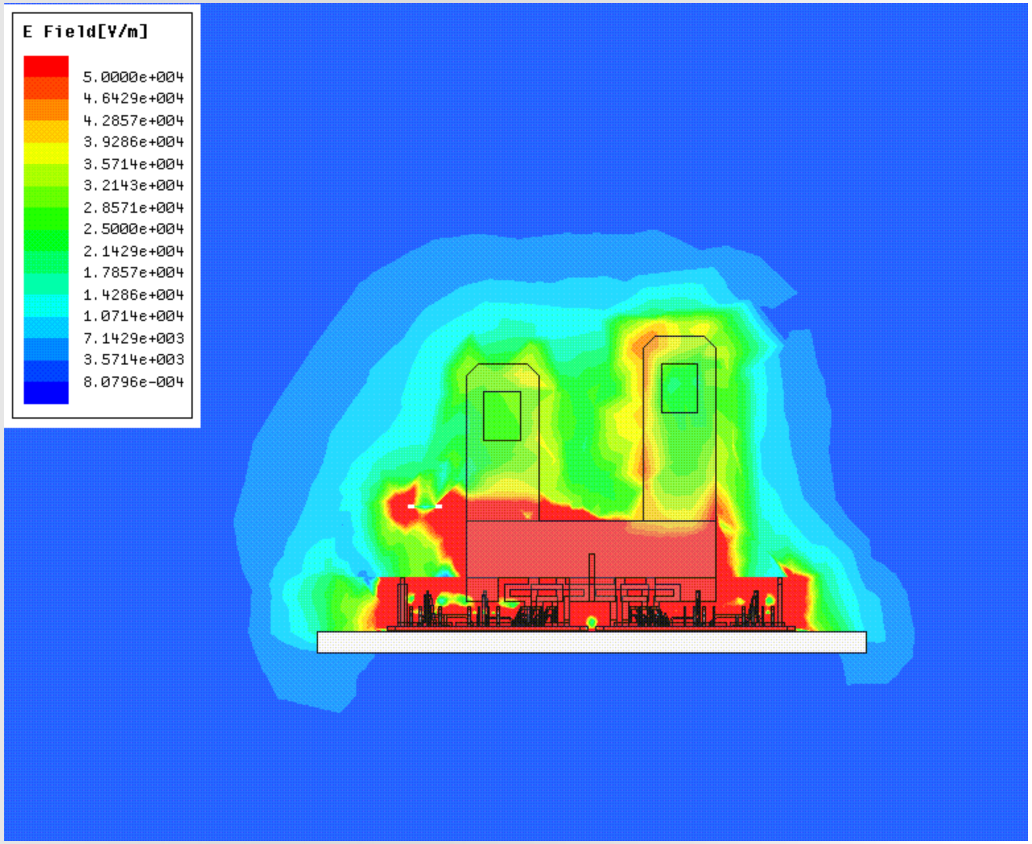
Spectrum from Simplorer

Outputs from Simplorer
Inputs for HFSS

Outputs From HFSS
(normalized results)

Fields Levels

Emitted Fields



mag E @ 100 MHz, Power = 10 000W

- The E field is very localized close to the module even at 100 MHz
- However, the very high power can lead to large values of E field even far from the module
- This design is fine at 110MHz.

Spectrum (MHz)	Power (W)	E field at 1m (V/m)
115.7024793	2308.359536	10.35553171

Part II: Multiphysics -- Outline

Context / Introduction

Component level Modeling

System level Modeling – Electrical Domain

Multiphysics Modeling - Workbench

Conclusions

Context/ Introduction

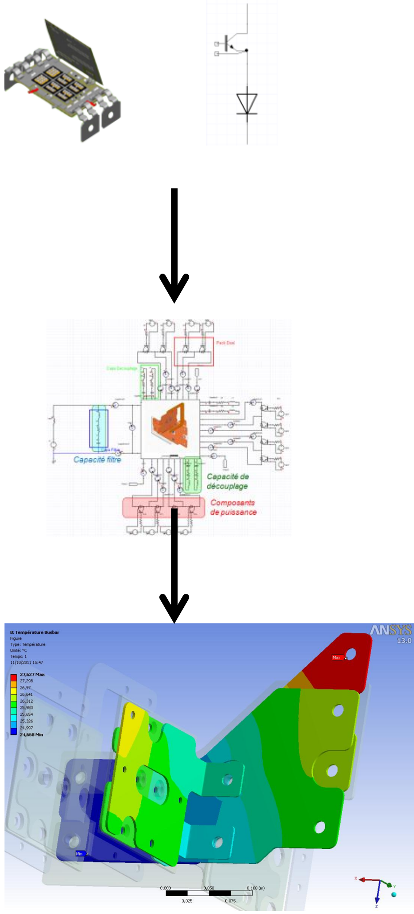
A (Power) Component is the combination of semi-conductors (IGBT, diodes, …) and associated BusBar or PCB. This presentation details how this component is designed:

1 – First stage consists in optimizing the geometry layout of the BusBars, Connectors, PCBs and finding the best Semiconductor types for a given specification.

- **This design is established with a pre-defined test circuit**
- **It's a mix of Electrical Modeling and 3D Modeling.**

2- Second stage consists in using this component in its real environment (loads, sources, actual waveforms) to determine the exact current waveform that are seen by the Component.

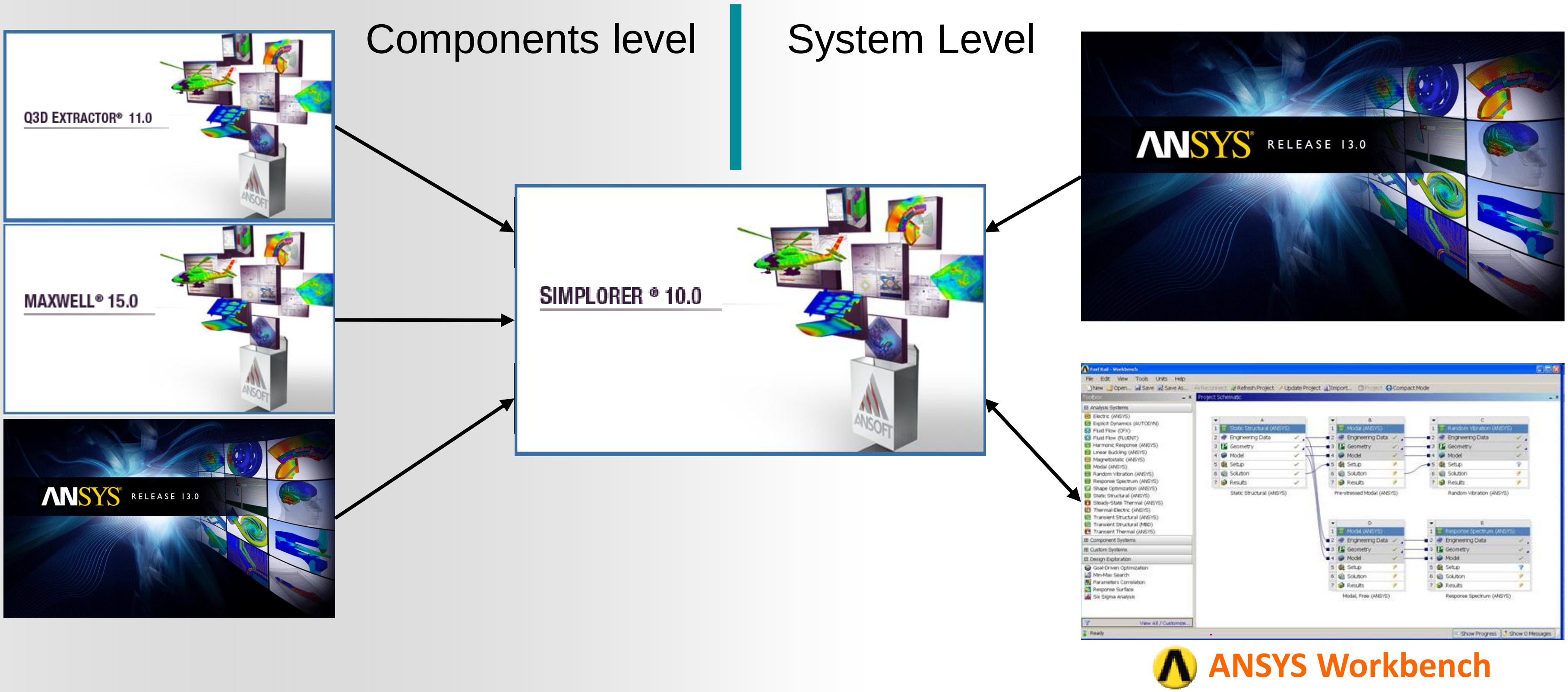
3 -Finally, The current waveforms are used as a source for a Electro-thermal-Mechanical analysis



Context/Introduction

Multi-physics Modeling is used at the component level and a the system level

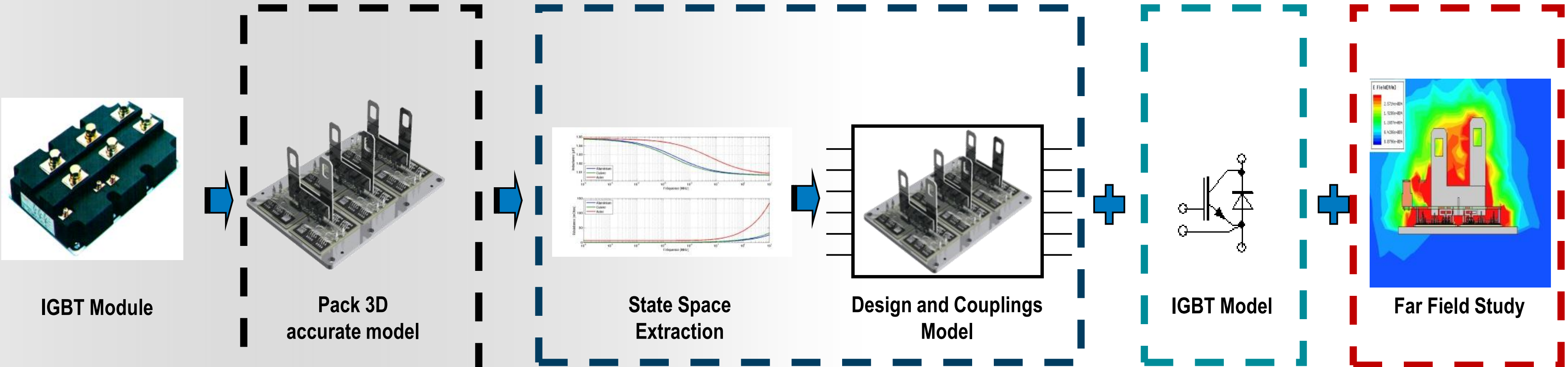
- Each physics is simulated with High Fidelity Solvers
- Workbench is used to couple the different physics
- Simplorer is used as a Power Electronics simulator and System integrator

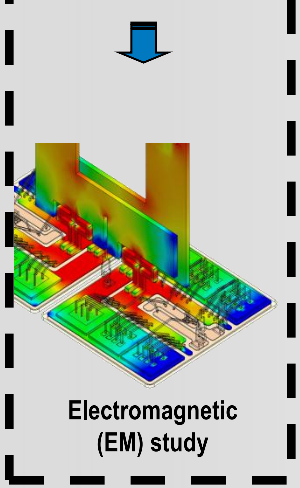


Component Level Modeling

Component Level Modeling

Example of EMC/EMI Oriented Model design developed at Alstom *



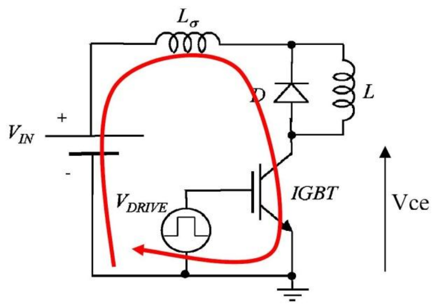


- **Tridimensional IGBT pack model and EM study**
- **State space extraction**
- **IGBT circuit model**
- **Far Field Study for Electric Field EM**

** Emmanuel Batista, Vincent Delafosse, «Simulating EMC/EMI Effects for High Power Inverter Systems », Ansoft Inspiring Engineering, 2008*

Component Level Modeling

« Double-pulse » tests and measurements are standard for validating components in the Train industry. The Busbar, the IGBT and Diode are characterized on a pre-defined test procedure.



Questions to be answered:

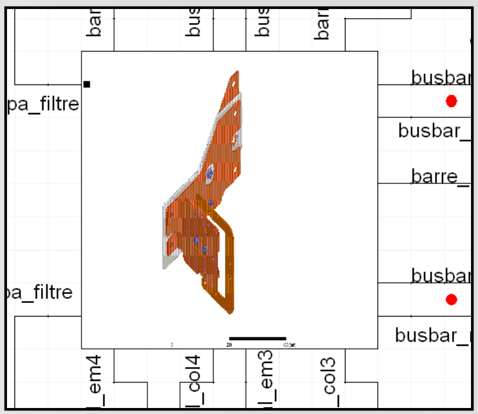
- **For an imposed IGBT type, what is the best Busbar layout ?**

We are able to perform virtual testing of these components combining :

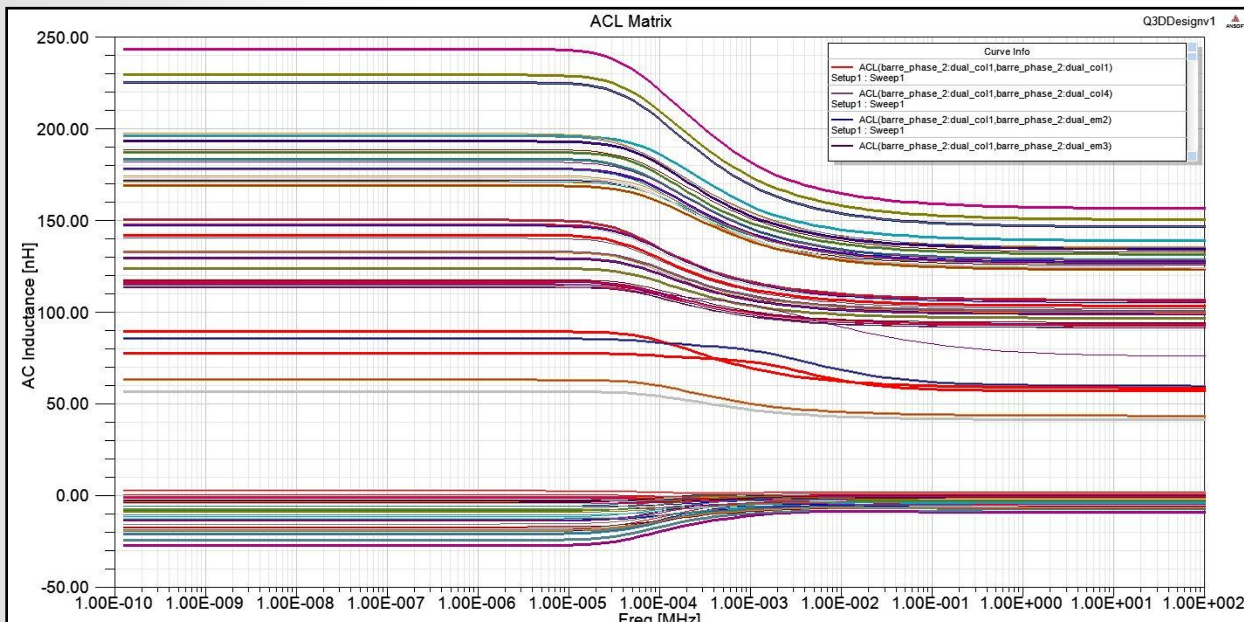
- **Circuit simulation for the Electrical Characteristics of semiconductors**
- **3D Modelisation of the RLC**

Component Level Modeling

The switching of these power modules are operated at “low frequency” (1kHz-20kHz). However, the highest frequency that we need to capture is related to the rising time of gate voltage. It’s about 10ns, therefore Q3D is solved up until 100MHz ($f_{\max} = \dfrac{1}{2 \times t_{sw}}$ **)**



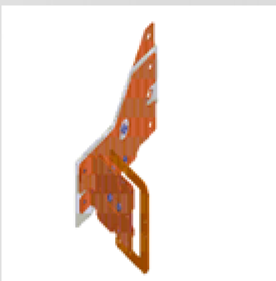
Several busbars geometries have been tested and measured



Component Level Modeling

We use ROM to capture electrical characteristics of the BusBar layout

Q3D

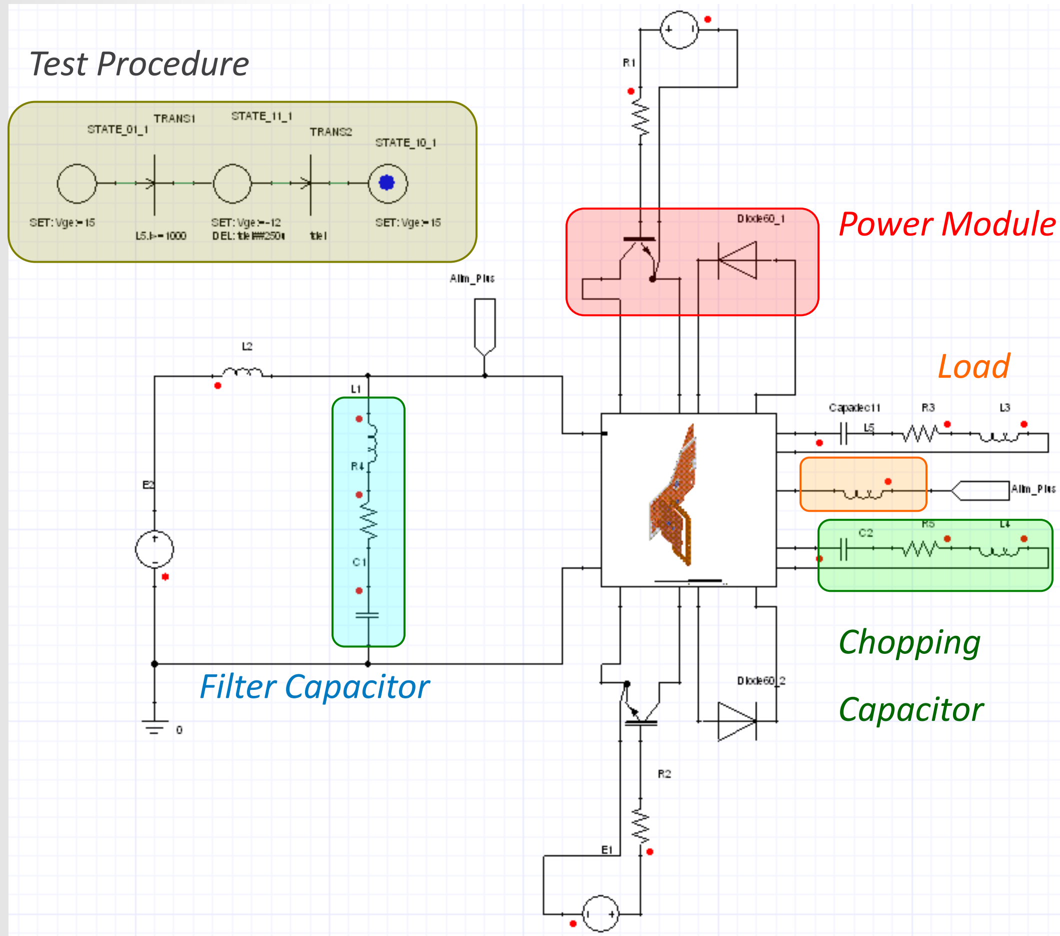


RLC Parameters

↓

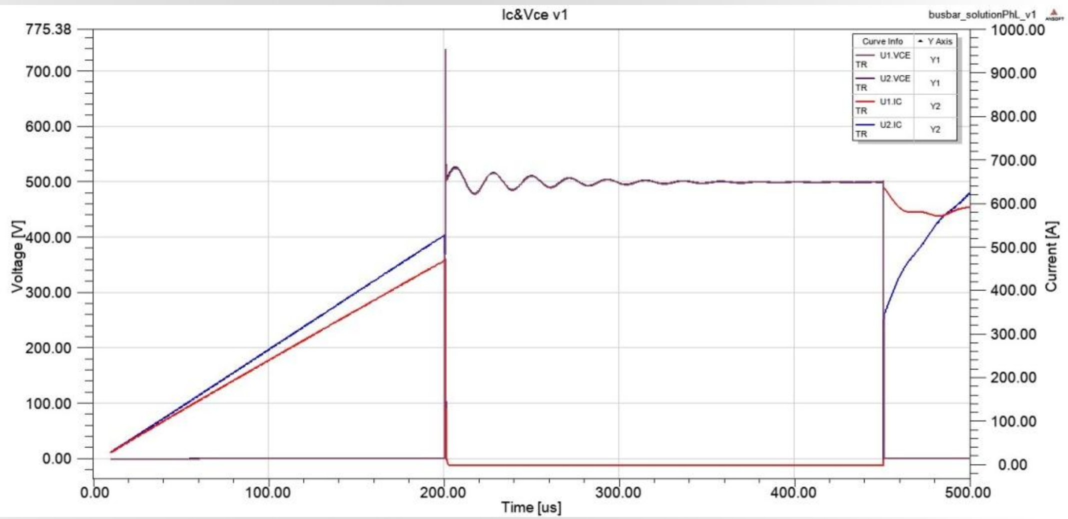
StateSpace Model

→



Component Level Modeling

This **virtual prototype** **of the power component enables Geometry validation of the busbar based on electrical criteria. It's a mix of 3D and circuit simulations.**



« Double-pulse » Virtual Test Results

<u>**Obtained Results:**</u>

Validation of the component

(IGBT/ Busbar layout)

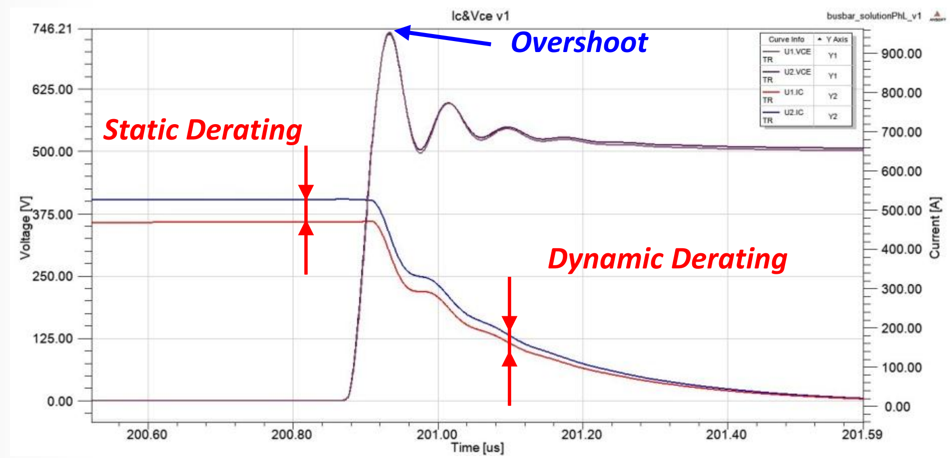
Component Level Modeling

Moreover, in train applications, power components are used in parallel as it is necessary to achieve high power requirements ad high reliability.

It is very easy to validate the power components in parallel in their system environment looking at:

•Overshoot, Oscillations, Losses, …

•Derating



Voltages /currents at the switch off of the IGBT

BUSBAR COMPARISON			Icom=1000A	Vbus=500V			
GEOMETRY	dI/dt [kA/µs]	dV/dt [kV/µs]	DV [V]	Lloop[nH]	Static Derating [%]		
1	*4*	*16*	*238*	*59.5*	*11*		
2	*4*	*15*	*186*	*46.5*	*11*		
3	*3.6*	*15*	*223*	*62*	*22*		

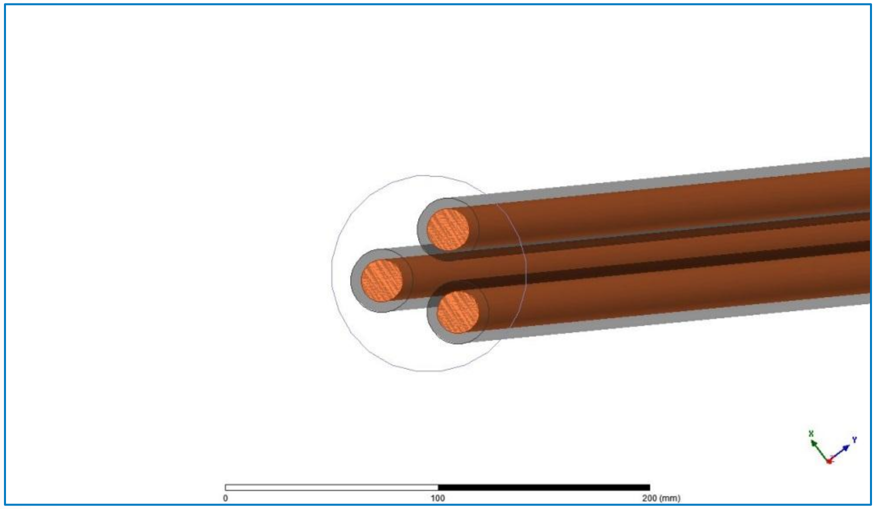
System level Modeling – Electrical Domain

System Level Modeling

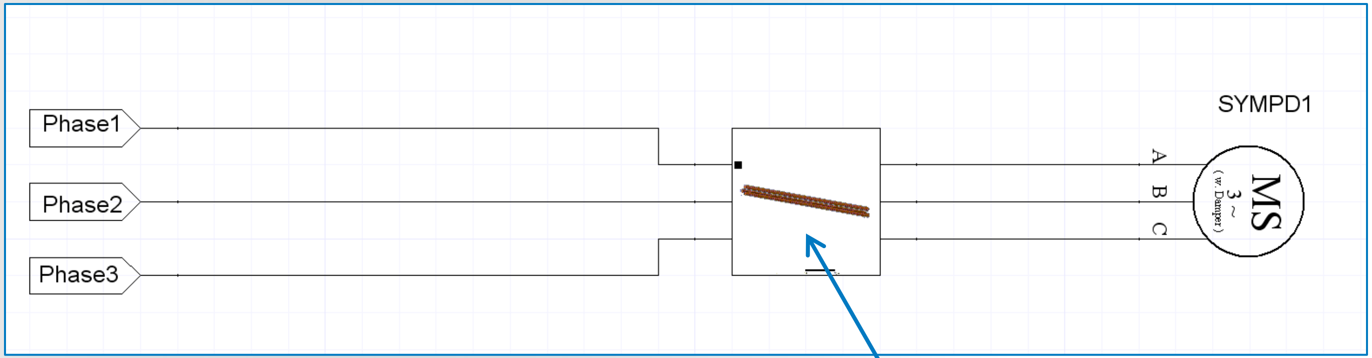
Power Cables Characteristics are simulated

Specifics of the Motor cables:

- **High Currents/ Low Frequency with almost sinusoidal at the Stator**
- **Very high dV/dt, Voltage Switching**
- **Forts dV/dt, Voltage-based PWM (MLI)**



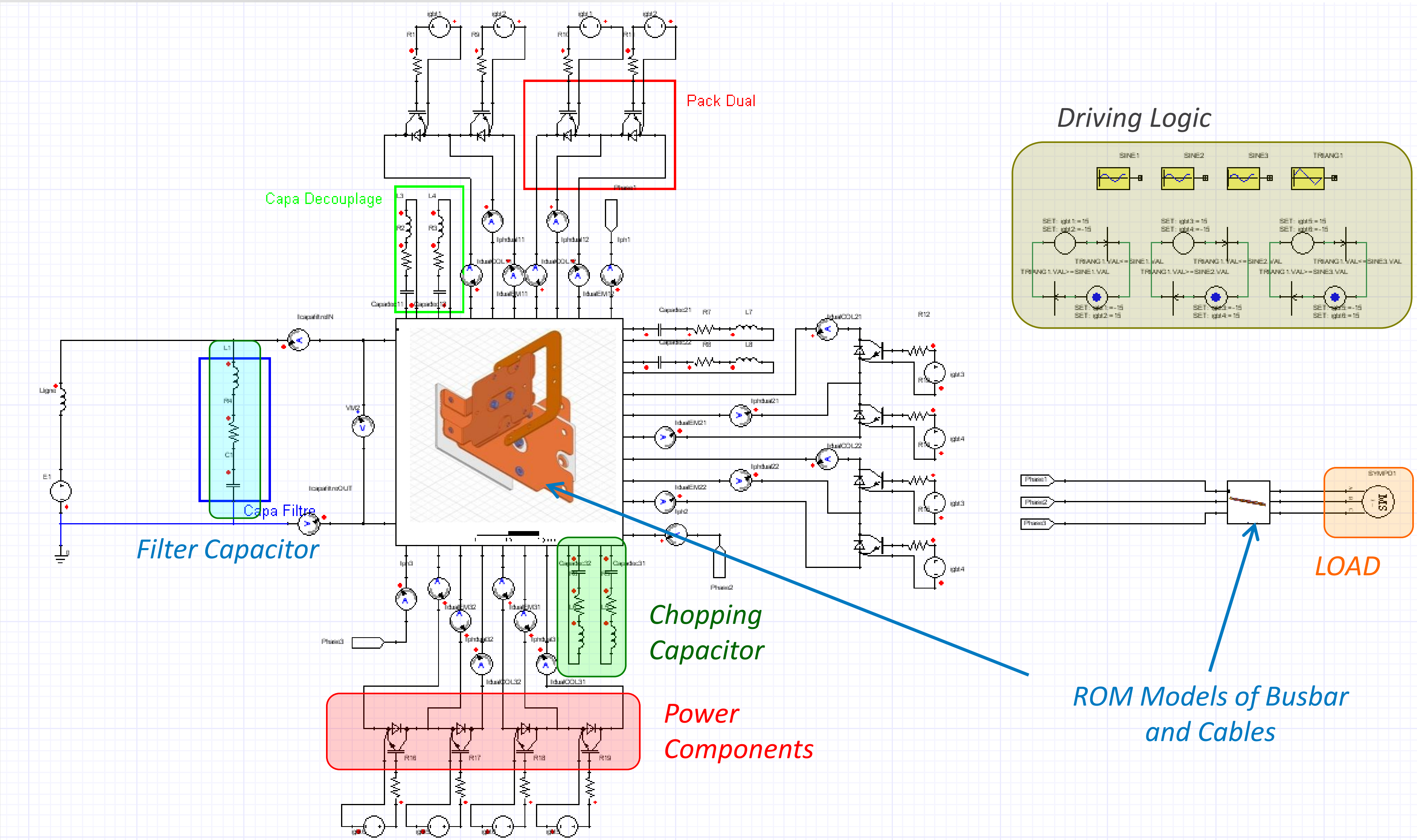
3D layout of the Cables



ROM models contain:

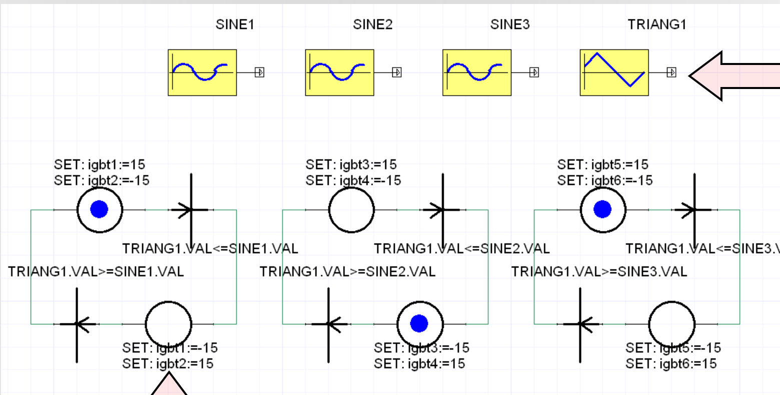
- Partial Inductances of Cables
- Capacitance effects are also included

System Level Modeling

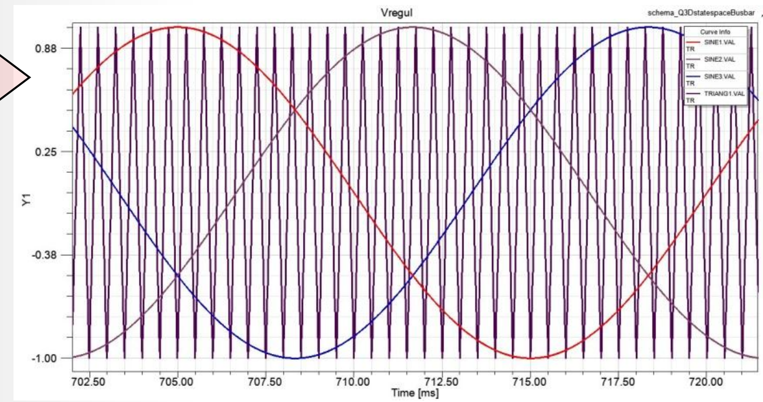


System Level Modeling

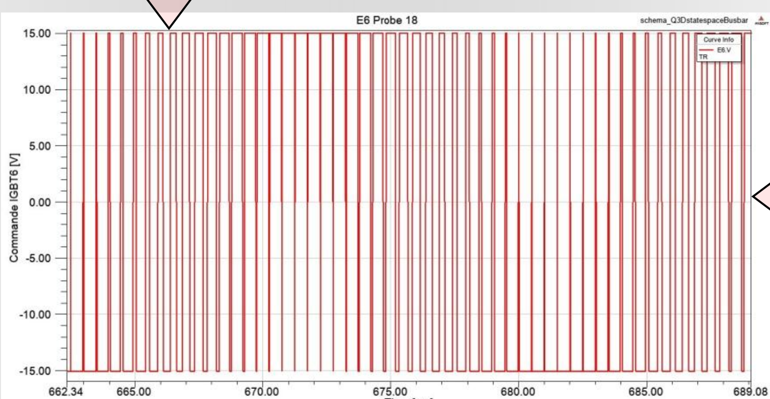
Voltage waveforms of the PWM



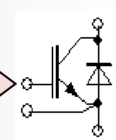
Switching events are defined with State Graphs



Asynchroneous PWM with Fcom>>10xFstat



Command signal applied at the IGBT gate



Average IGBT is used because:

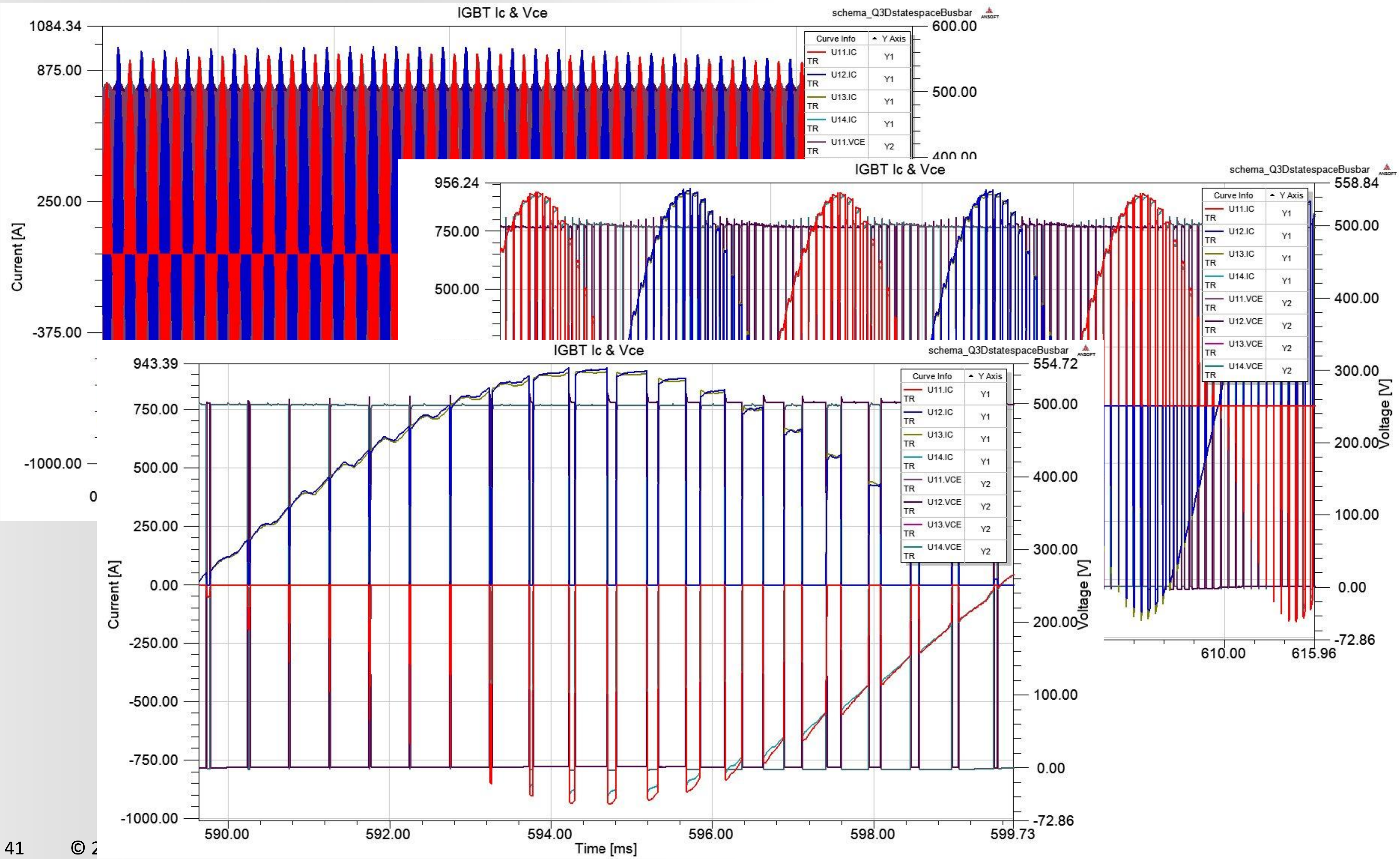
- **Very long simulation: t > 1 s**
- **We don't need switching details**
- **Switching losses are fitted to the datasheet values and measured values.**

Références

1. **Pierre Solomalala, Emmanuel Batista, « Différents aspects de la modélisation multi-physique au sein du laboratoire PEARL/PRIMES », UGM ANSYS, 2009.**
2. **Emmanuel Batista, Vincent Delafosse, «Simulating EMC/EMI Effects for High Power Inverter Systems », Ansoft Inspiring Engineering, 2008.**

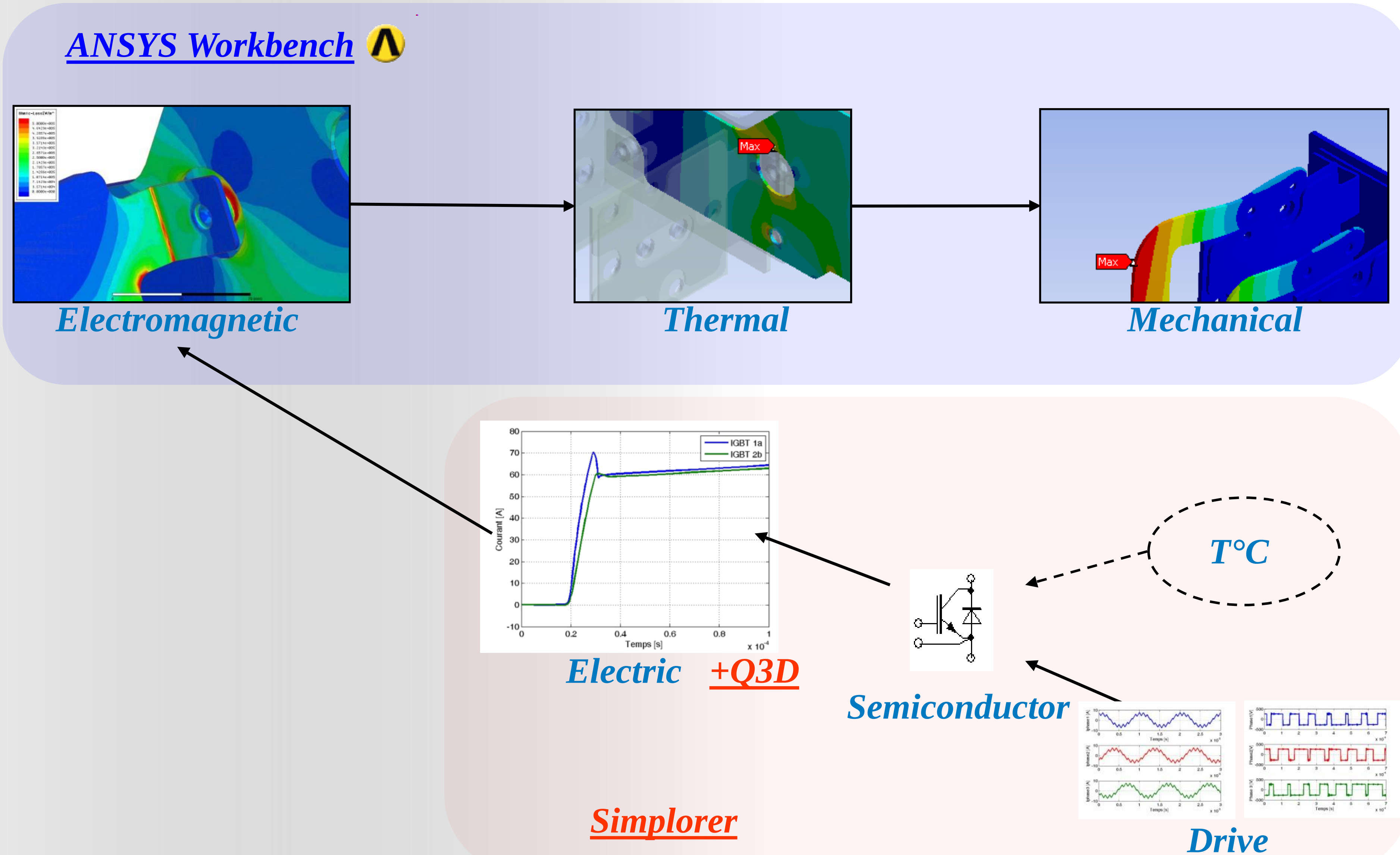
System Level Modeling

Some Results



Multiphysics Modeling in Workbench

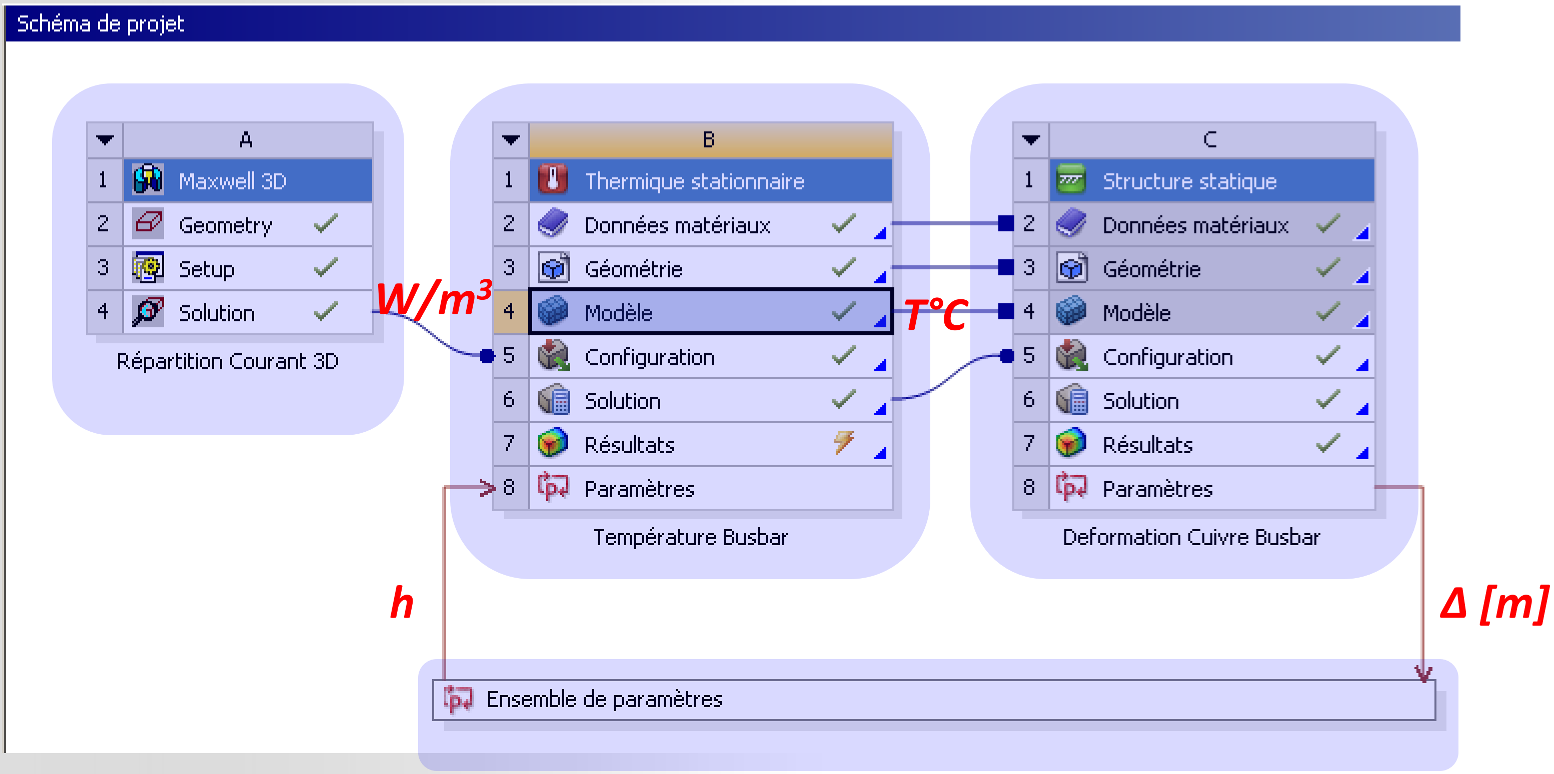
Multiphysics Modeling



ANSYS

Multiphysics Modeling

Workbench enables a seamless 3D coupling flow.

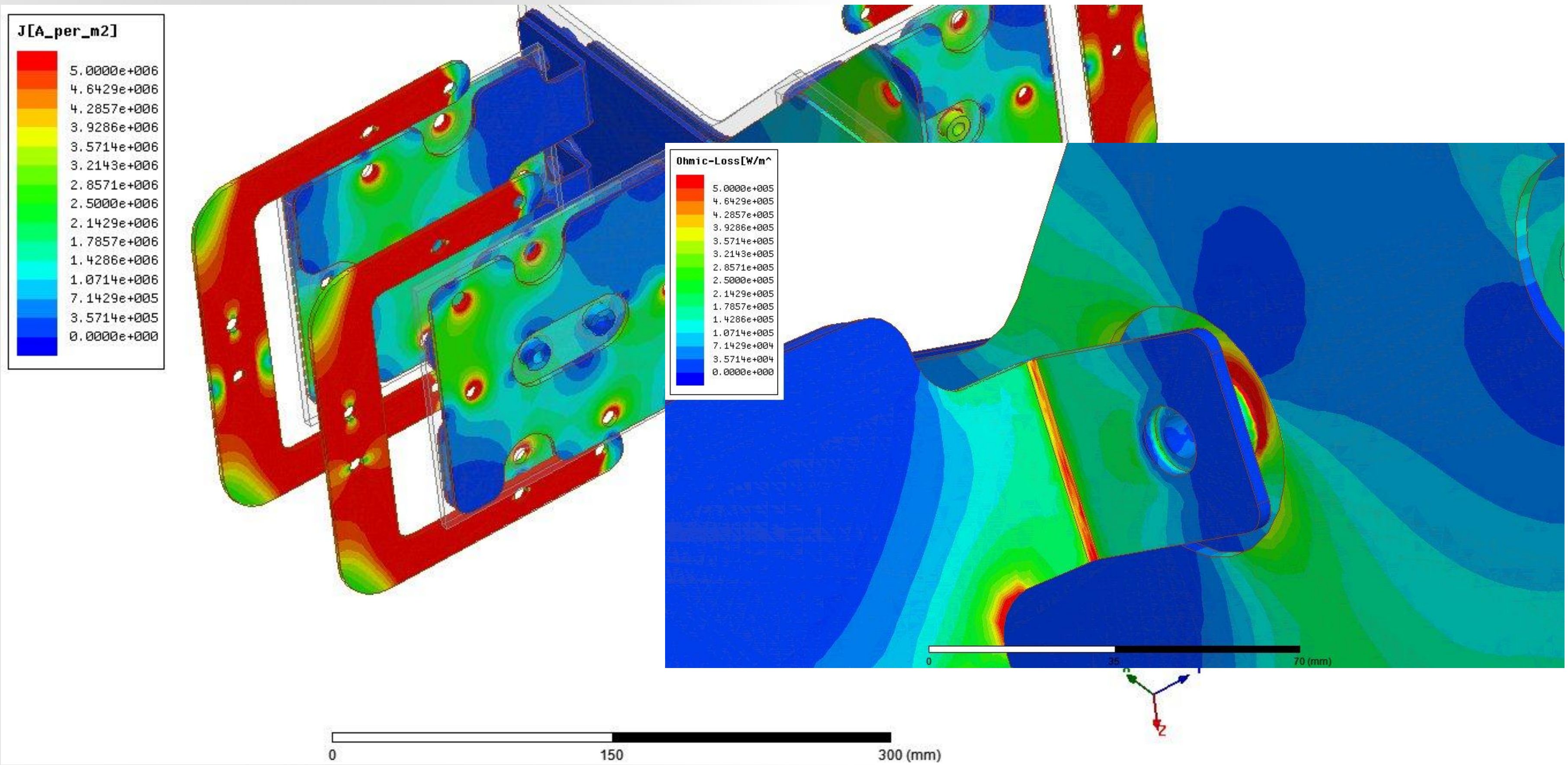


A parameter Analysis is used to determine what insulation material is needed to achieve a maximum displacement level

Multiphysics Modeling

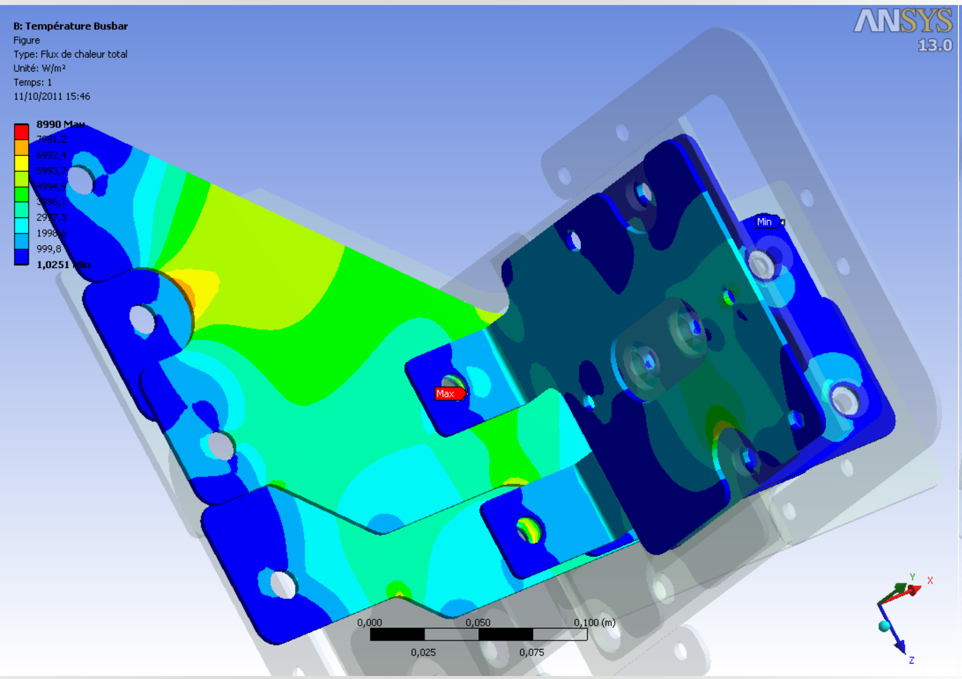
Maxwell 3D simulation: Current Calculation

- **Input: average current that is computed in the system simulation in Simplorer**
- **Output: Ohmic losses are calculated based on the volumic current calculations.**

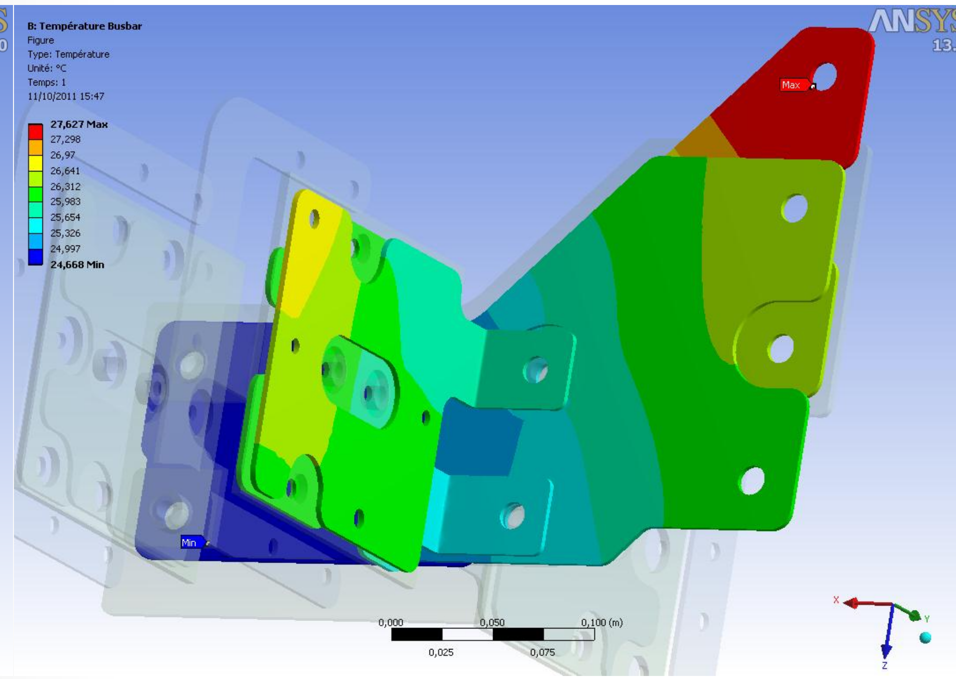


Multiphysics Modeling

Static Thermal Module of ANSYS: Temperature distributions



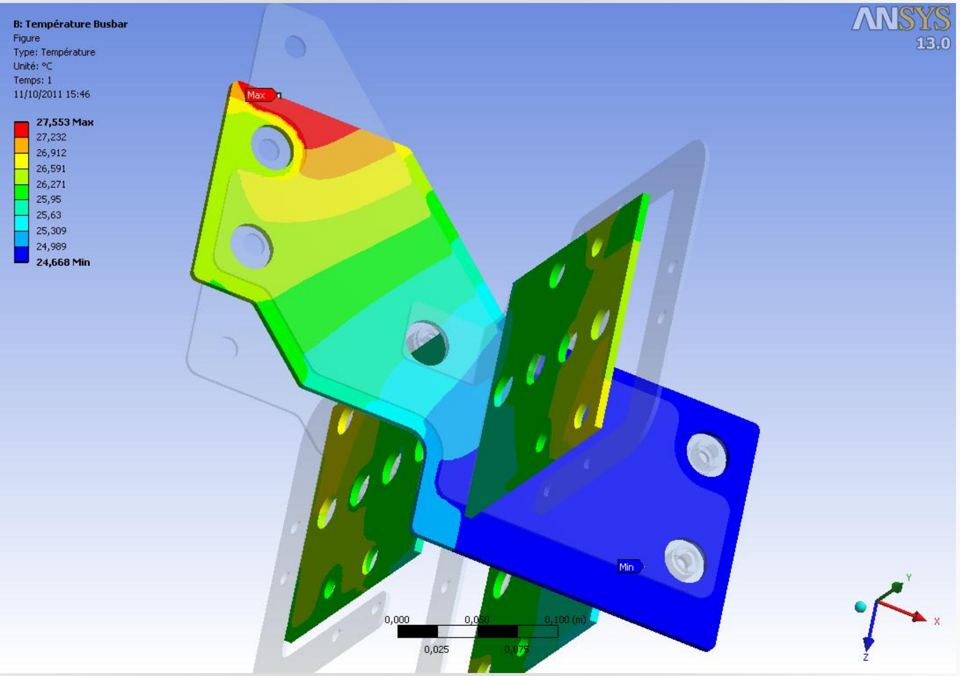
Heat Flux on Copper parts



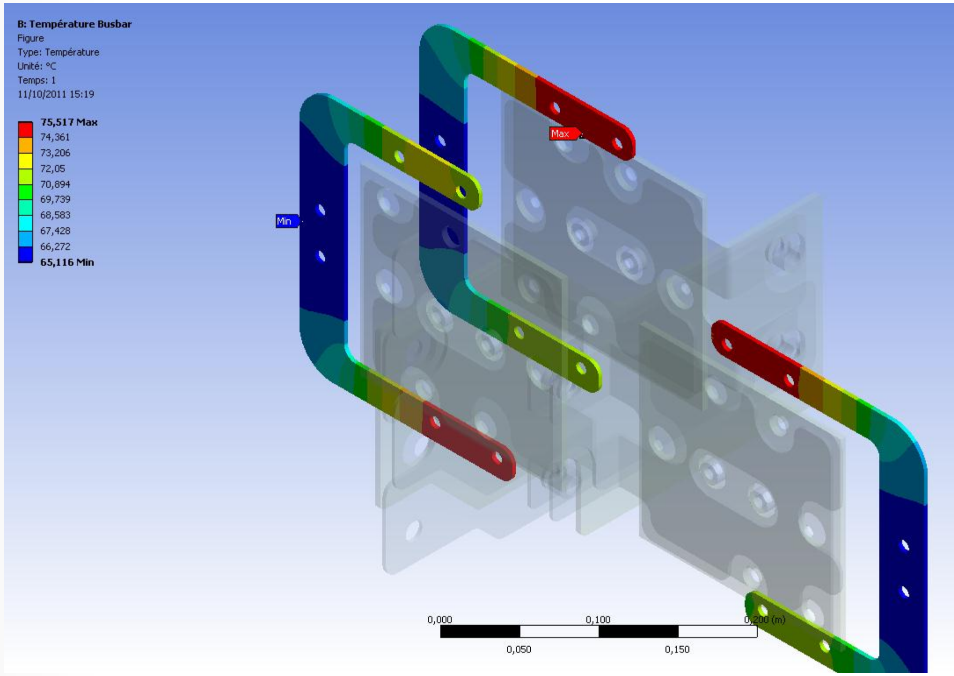
Maximum temperature on Copper parts

Multiphysics Modeling

Static Thermal Module of ANSYS: Temperature distributions



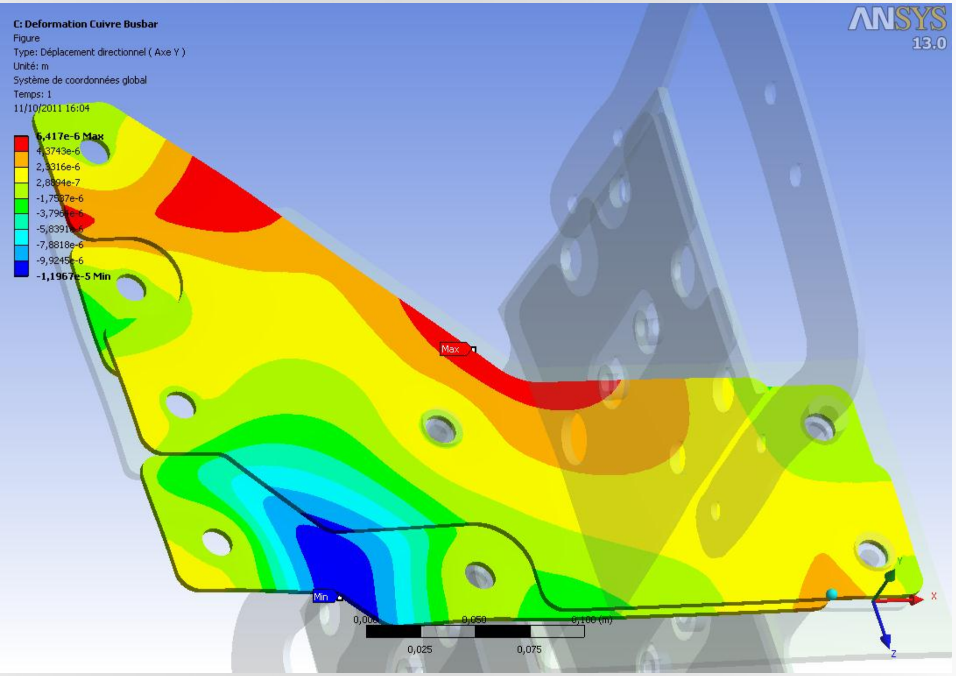
Insulation part Temperatures



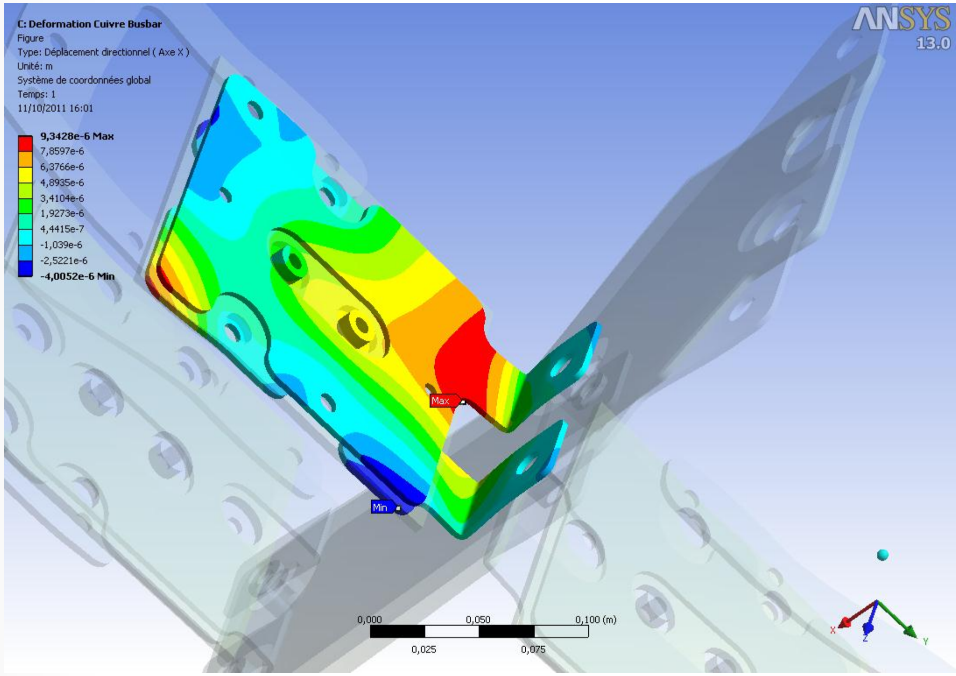
Phase Conductors Temperatures

Multiphysics Modeling

Static Stress Analysis



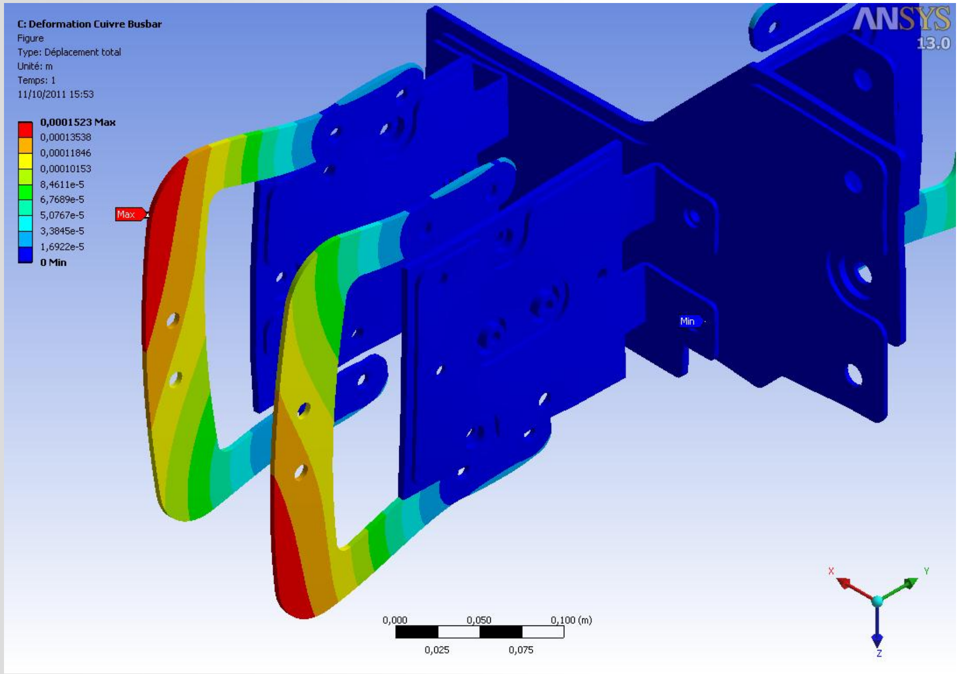
Y axis Displacements



X axis displacements

Multiphysics Modeling

Static Stress Analysis



Total Displacements

Conclusion

- A Multi-physics Multi level modelisation method has been presented
    - Dynamic IGBTS have been used at the component level
    - Average IGBT have been used at the system level
- State Graphs enable easy development of the command algorithm used to drive each inverter
- The Stress values are accurate as we have loaded the structure with real waveforms from system analysis.

THANK YOU

