Accurate SiC simulation in SPICE and plecs

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Bodo‘s
Wide Bandgap
Event 2024

Making WBG Designs Happen

SiC

Content

- onsemi Unique Physical & Scalable Simulation Modeling
- Are passives really passive ?
- SPICE simulations : Boost example
- onsemi online tool structure : 2 in 1
- Why a plecs Model Generator ?
- Data set density
- plecs model results
- Elite Power Simulator
- Comparing Boost results SPICE vs Custom plecs models
- Conclusions

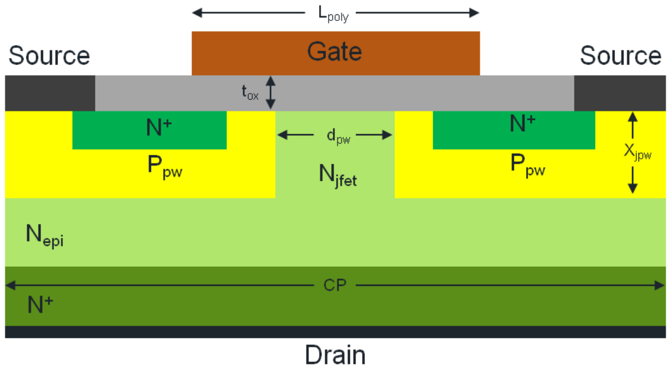
onsemi Unique Physical & Scalable Simulation Modeling

For accurate results in all conditions

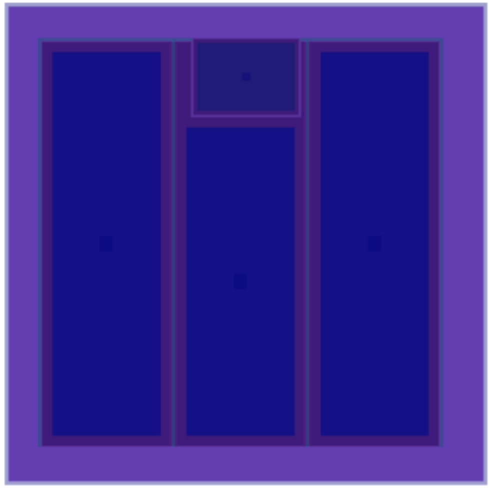
Physical & Scalable SiC MOSFET Models

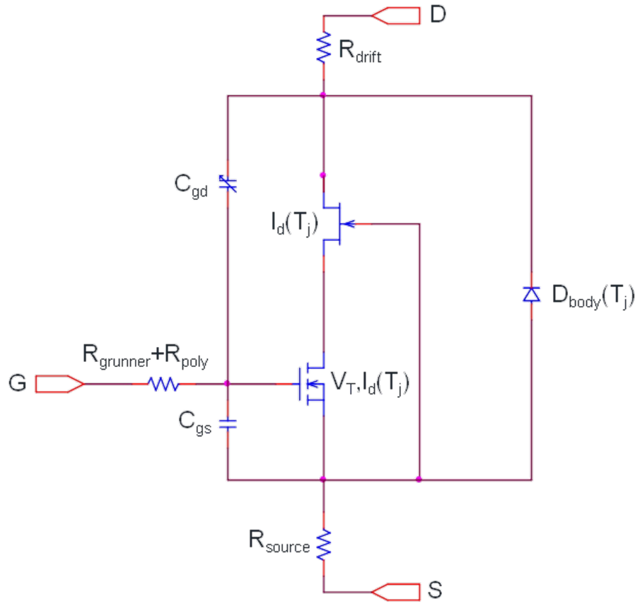
- Models are derived from physics-based formulations.
  - Published in APEC 2017
- Extensive verification to hardware performed.
- Design new devices through sizing and layout configuration.

Device Technology



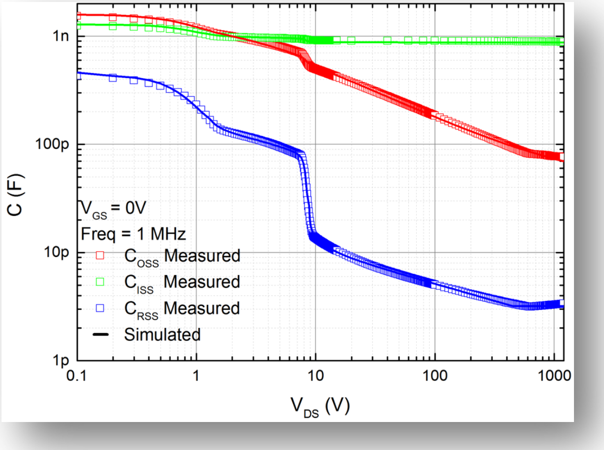
Layout/GDS



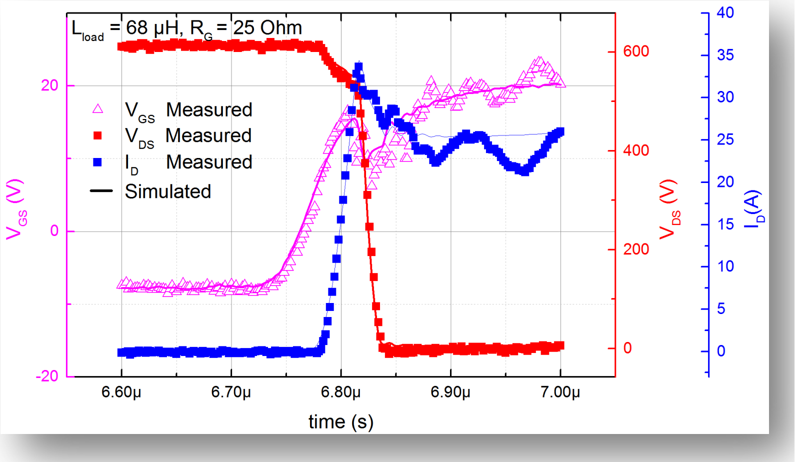


Physical Structure

Physical & Scalable SPICE Model



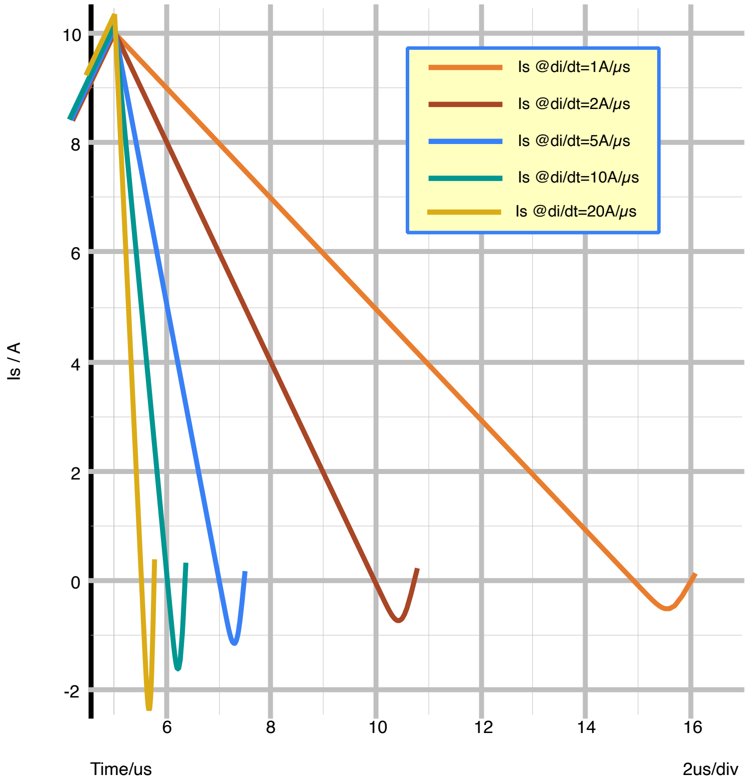
Models can predict static and dynamic behaviors



Comparison of various SiC MOSFET SPICE models

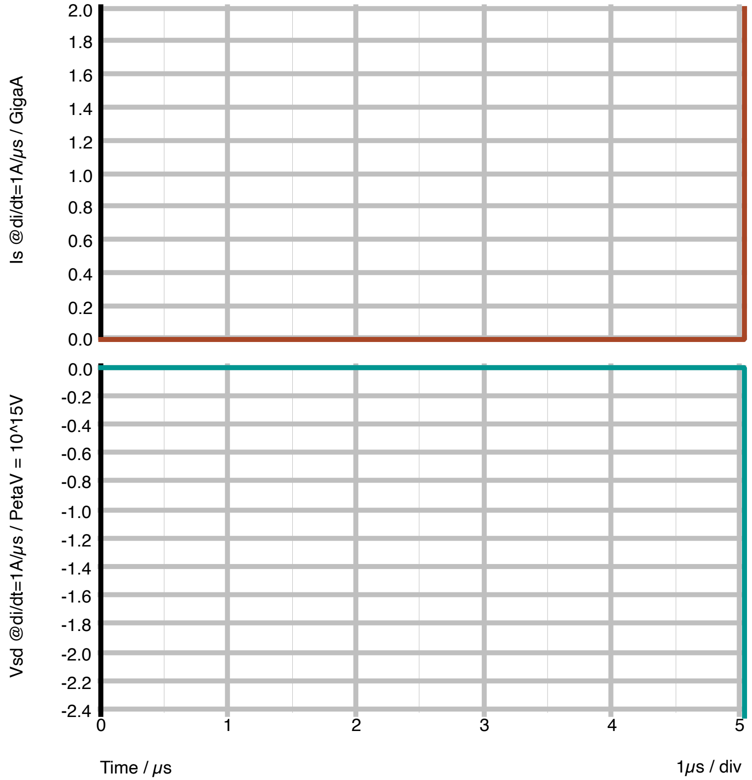
- Reverse Recovery vs di/dt :

NTH4L020N120SC1



Fine

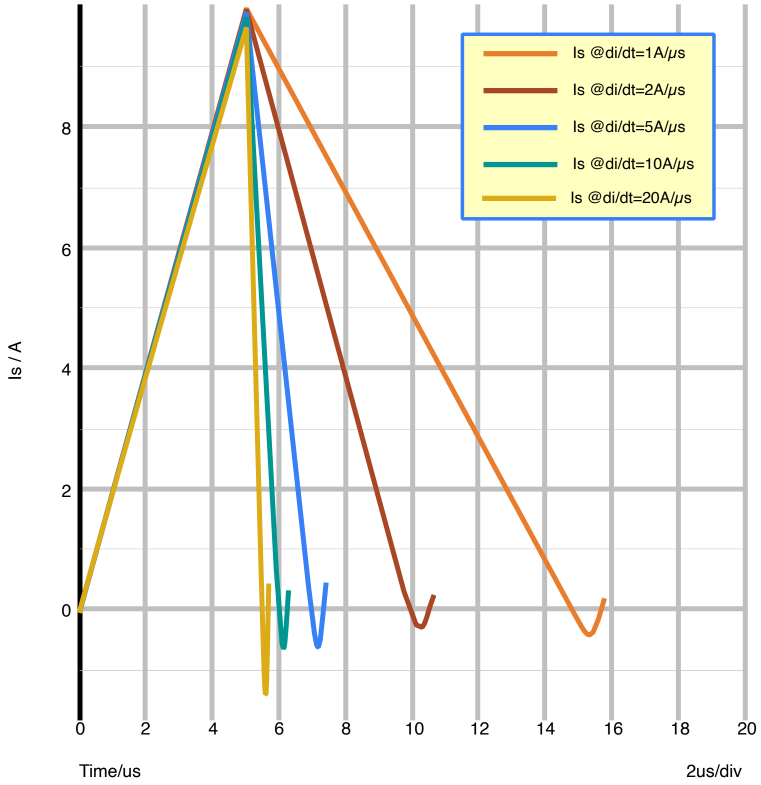
Competitor 1



Not able to simulate

& no Breakdown voltage

Competitor 2



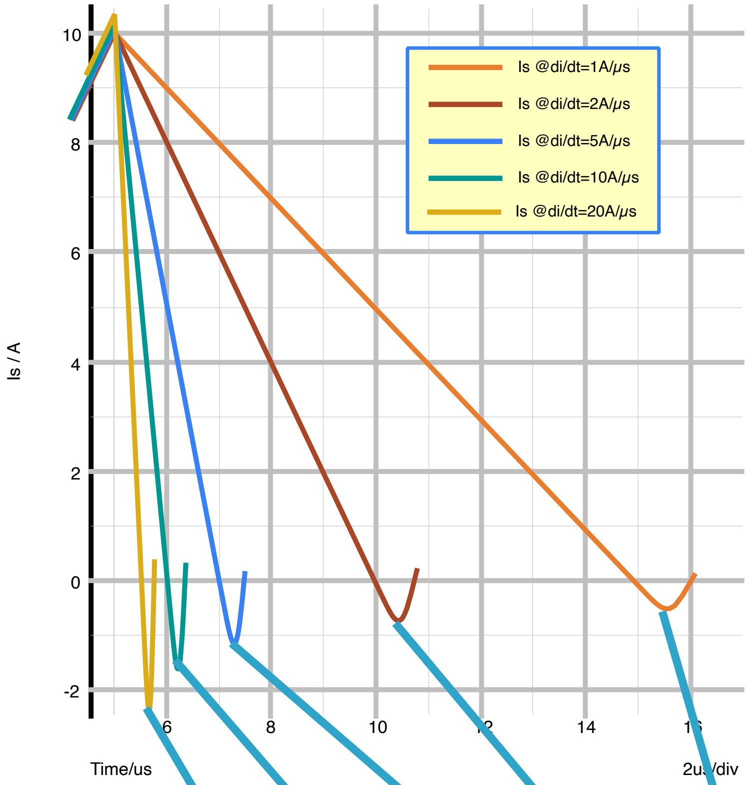
I_{RR}@5A/μs = I_{RR}@10A/μs

I_{RR}@1A/μs > I_{RR}@2A/μs

Comparison of various SiC MOSFET SPICE models

- Reverse Recovery vs di/dt :

NTH4L020N120SC1



di/dt (A/μs)	20	10	5	2	1
$I_{RR(peak)}$ (A)	2.3	1.6	1.1	0.7	0.5

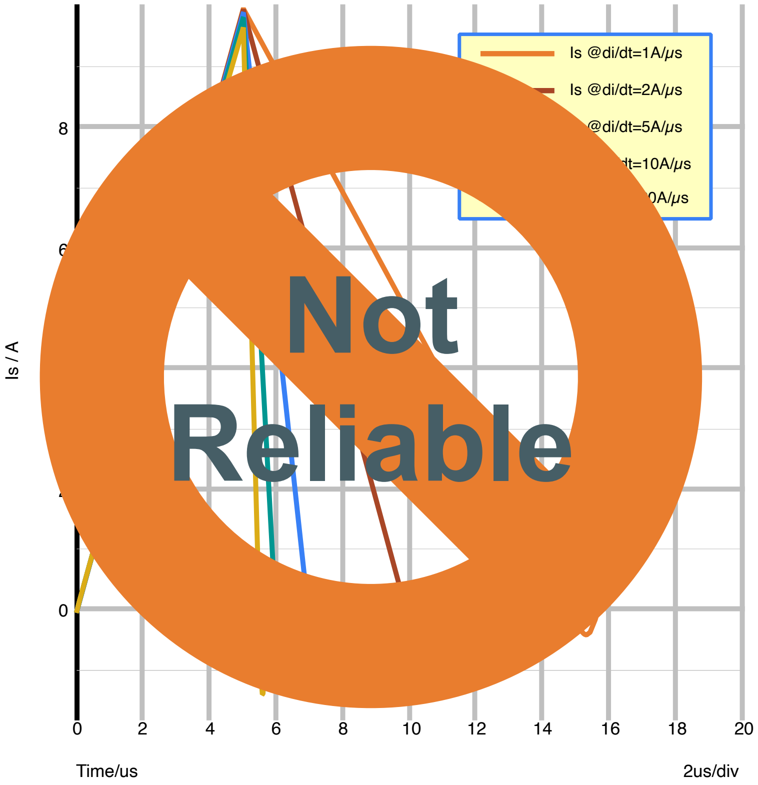
You can measure I_{RR} values

Competitor 1

Not able to simulate

& no Breakdown voltage

Competitor 2



I_{RR}@5A/μs = I_{RR}@10A/μs

I_{RR}@1A/μs > I_{RR}@2A/μs

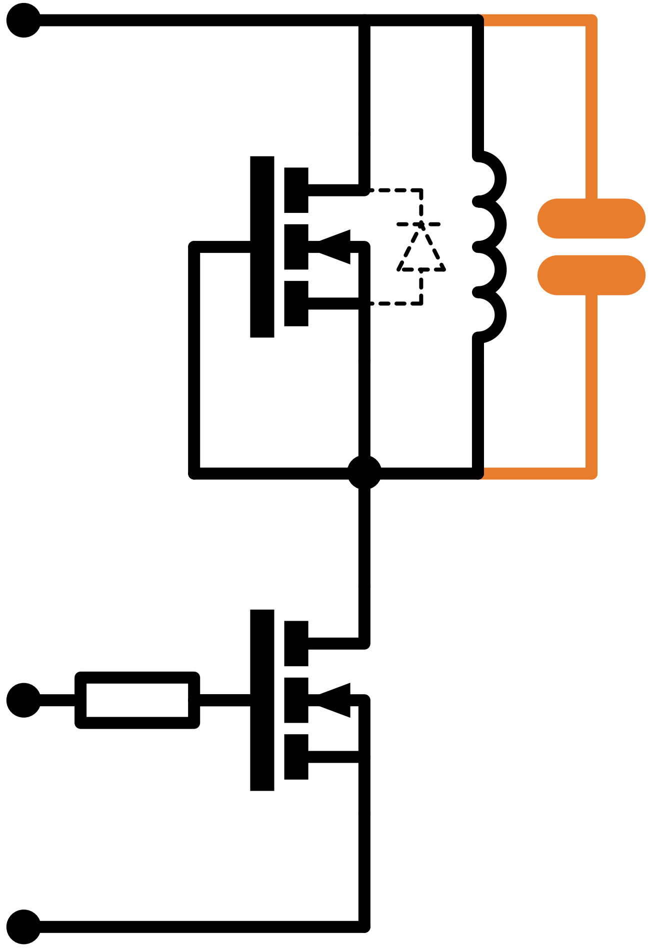
Are passives really passive?

How passive devices affect active device losses ?

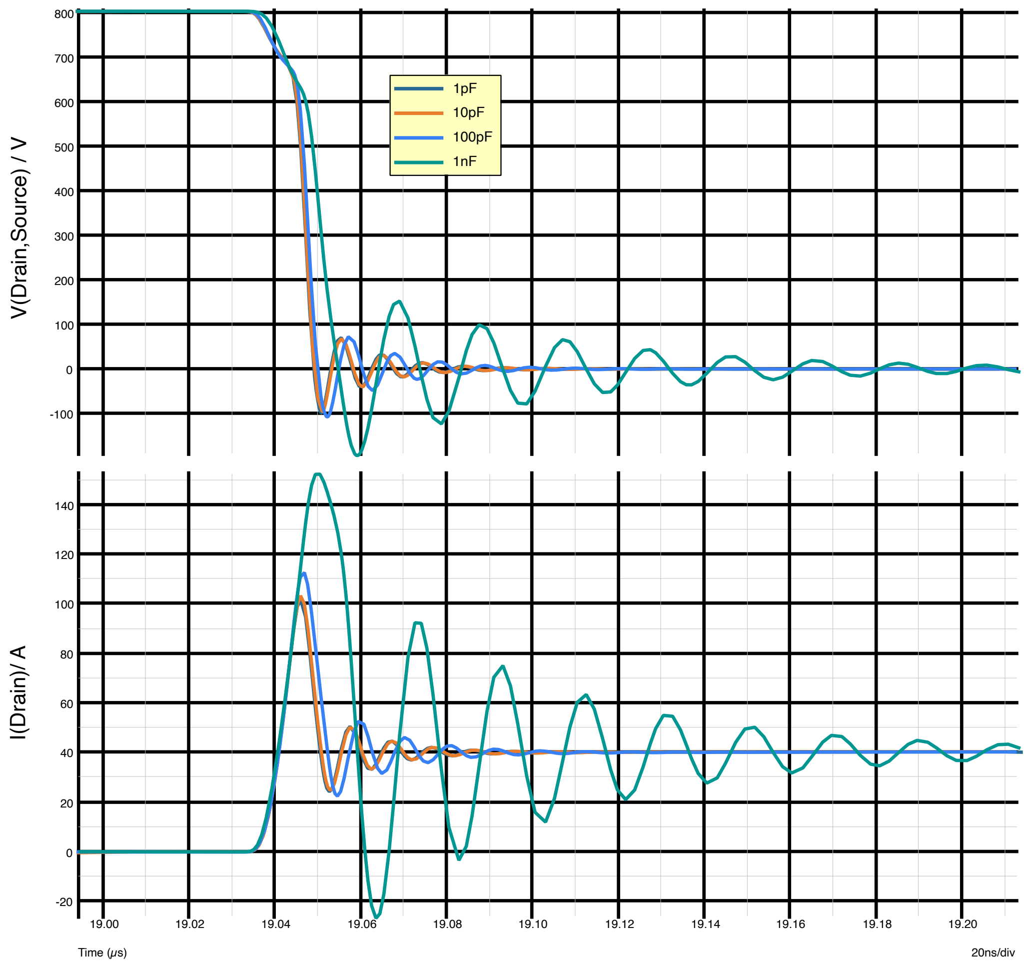
Various Parasitics Effects on Losses

Inductor Parasitic Capacitor

- **Schematic**



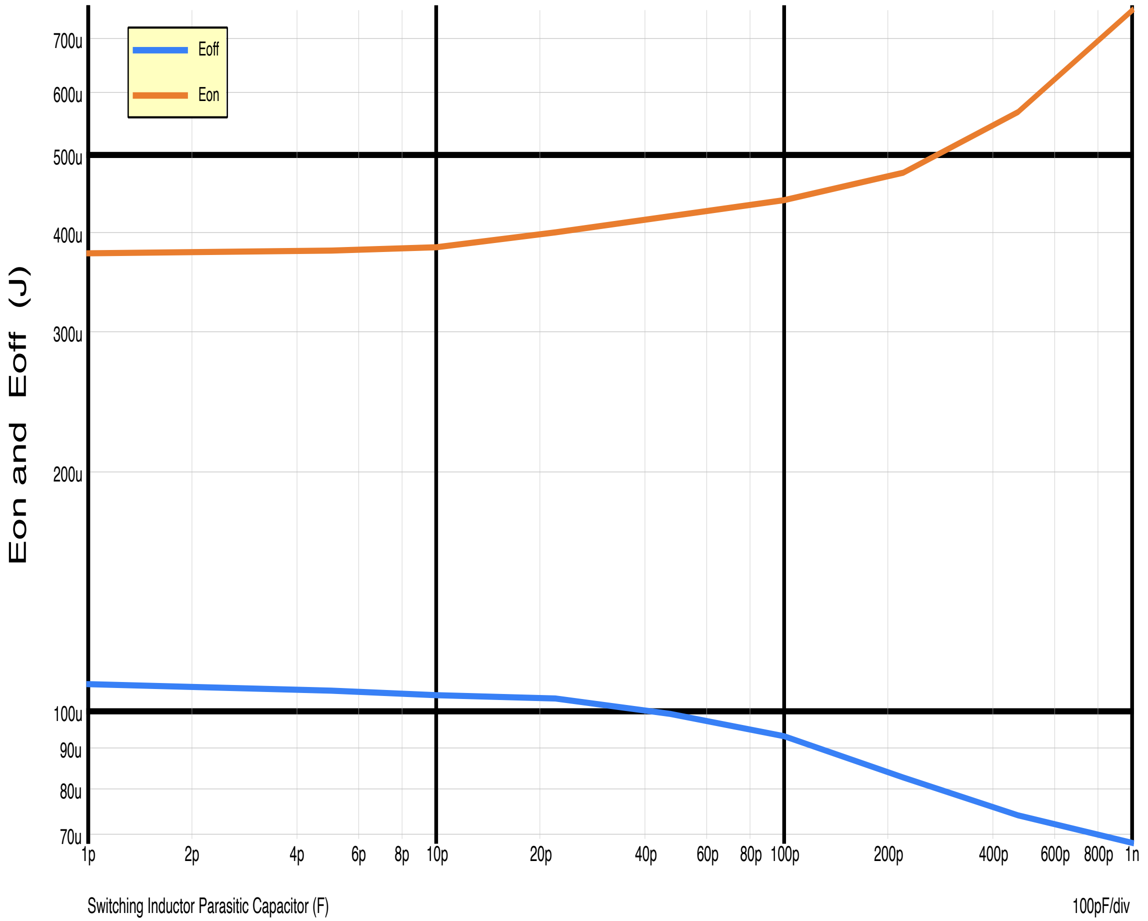
- **Turn-On Waveforms**



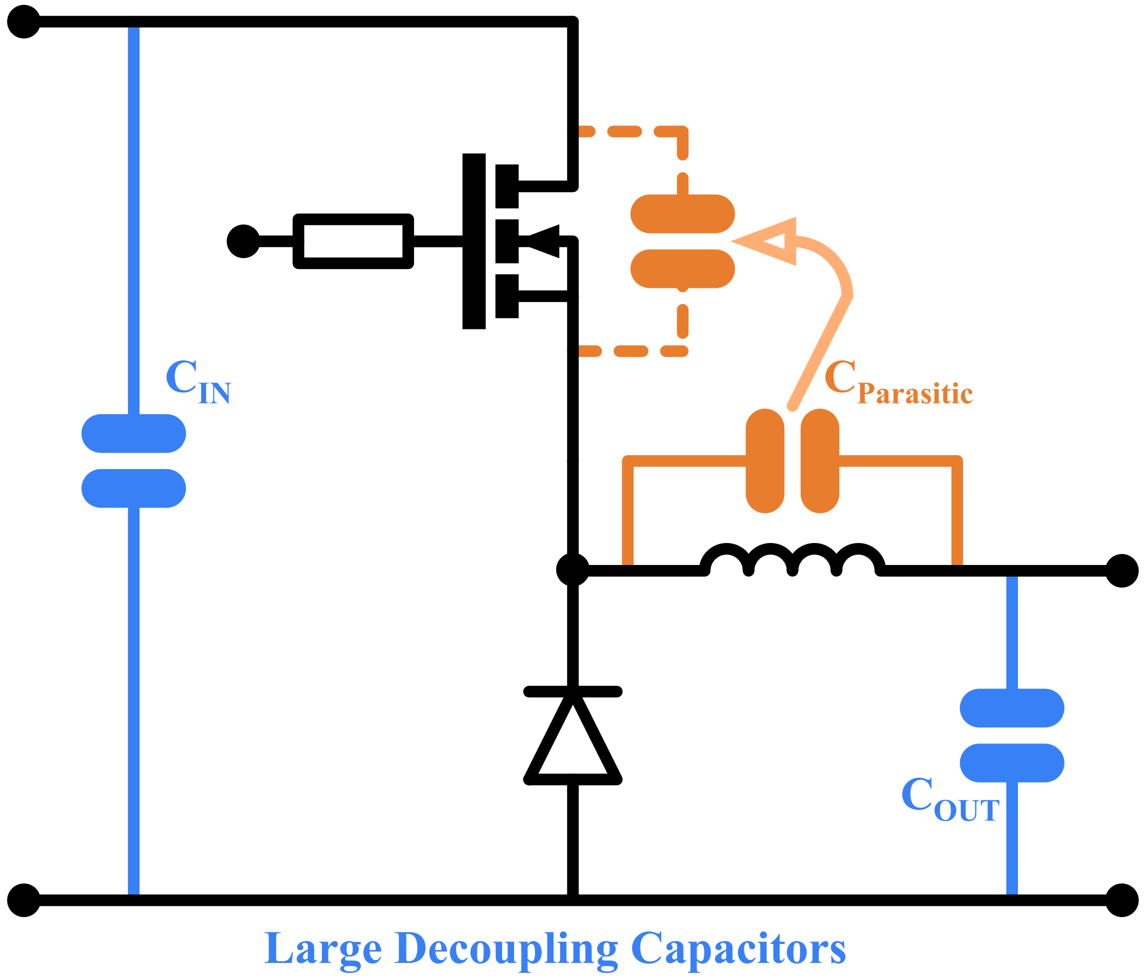
Various Parasitics Effects on Losses

Inductor Parasitic Capacitor

- **Eon & Eoff**



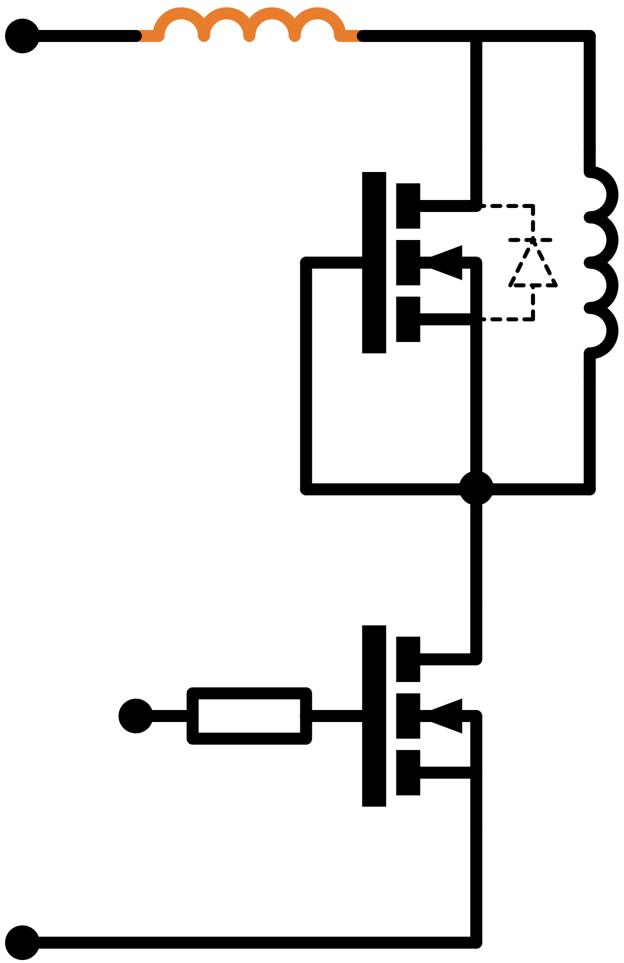
- **Equivalent Schematic**



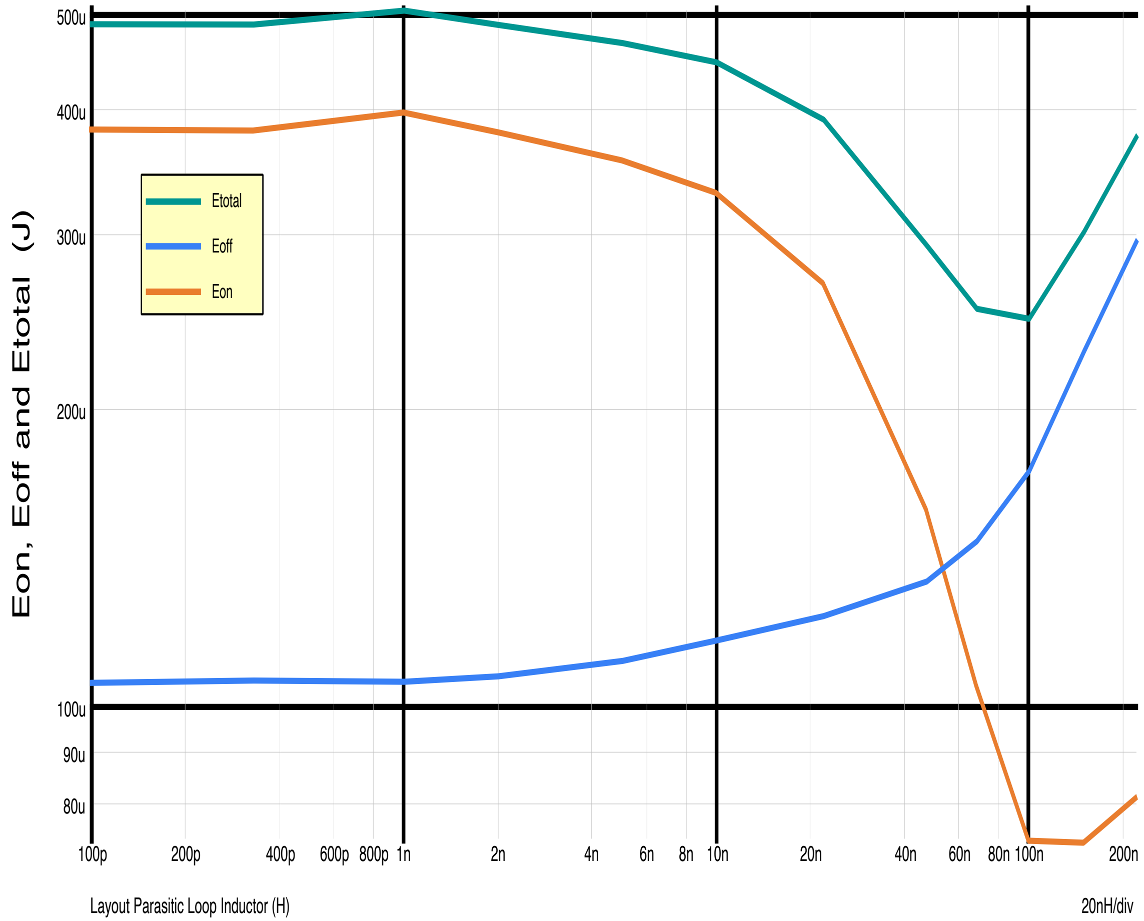
Various Parasitics Effects on Losses

Layout Parasitic Inductor

- **Schematic**



- **Eon, Eoff & Etotal**

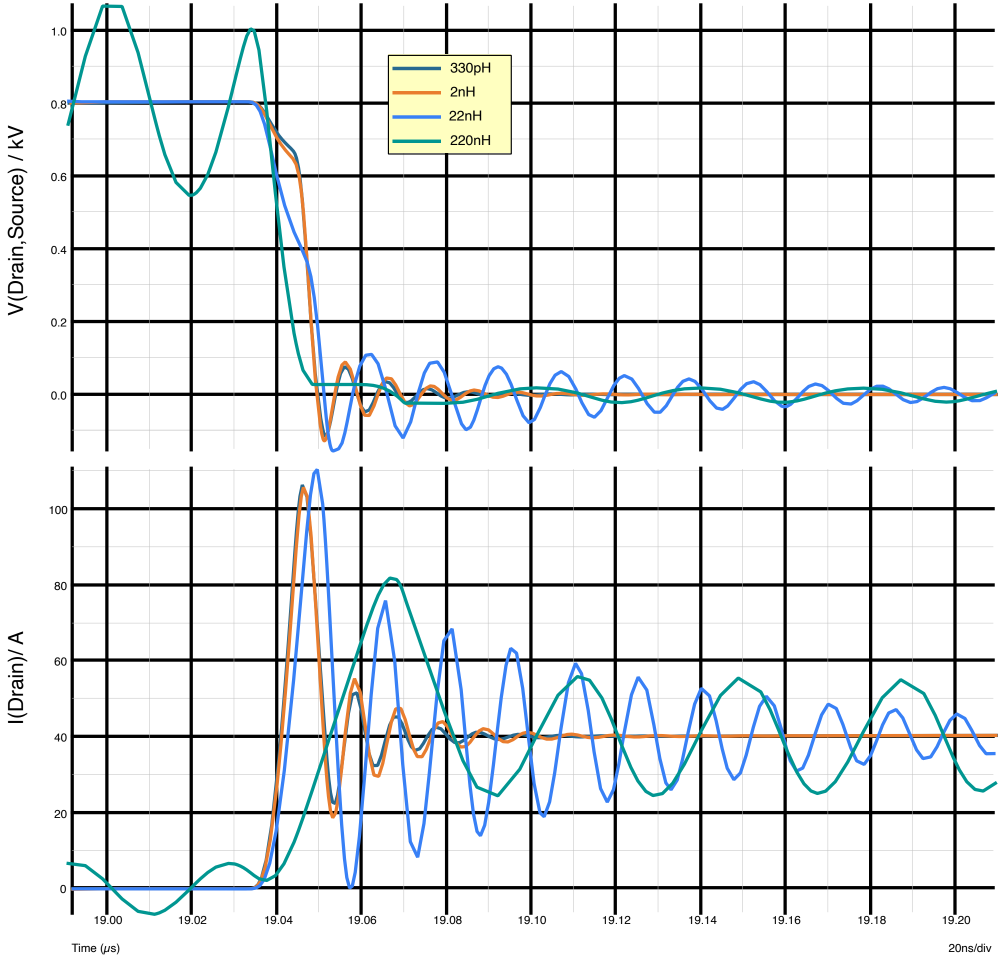


Various Parasitics Effects on Losses

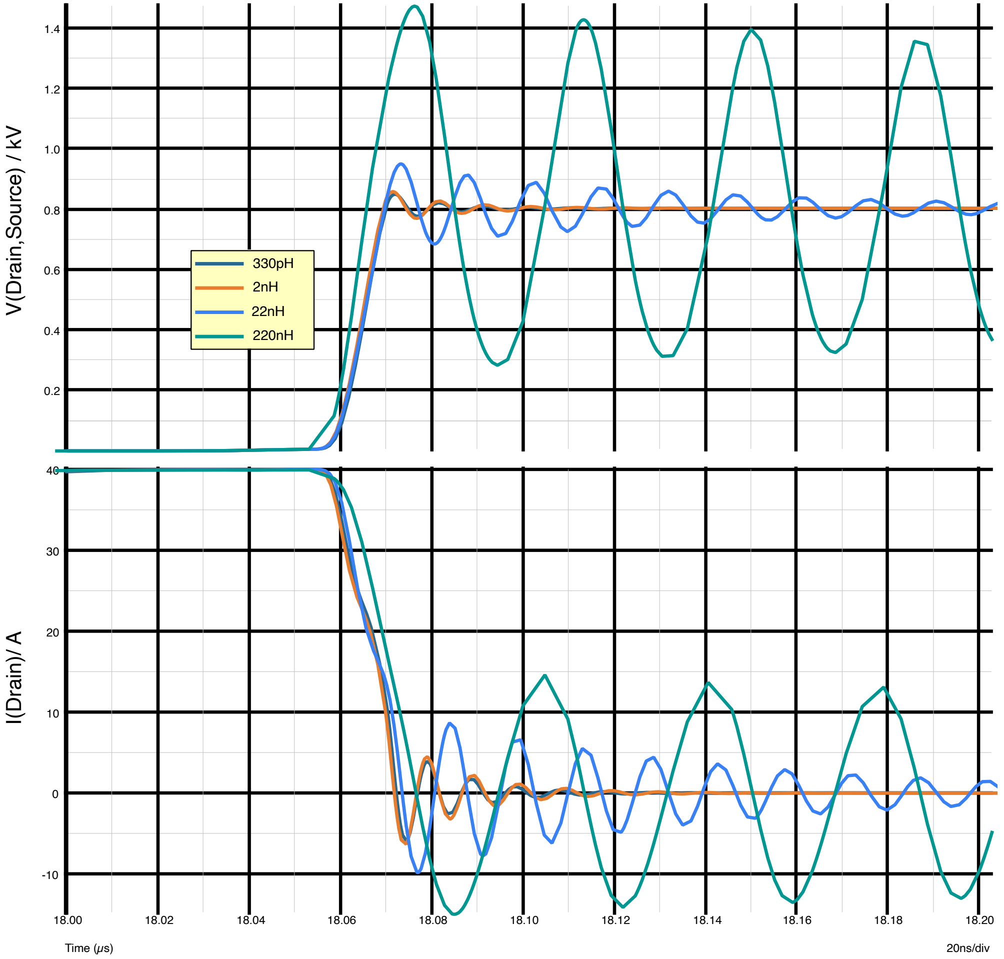
Layout Parasitic Inductor - Waveforms

Too much EMI with 22nH and 22nH

- **Turn ON**



- **Turn Off**

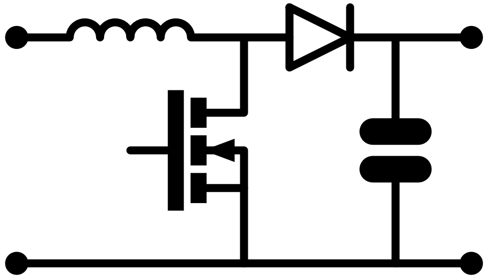


SPICE simulations

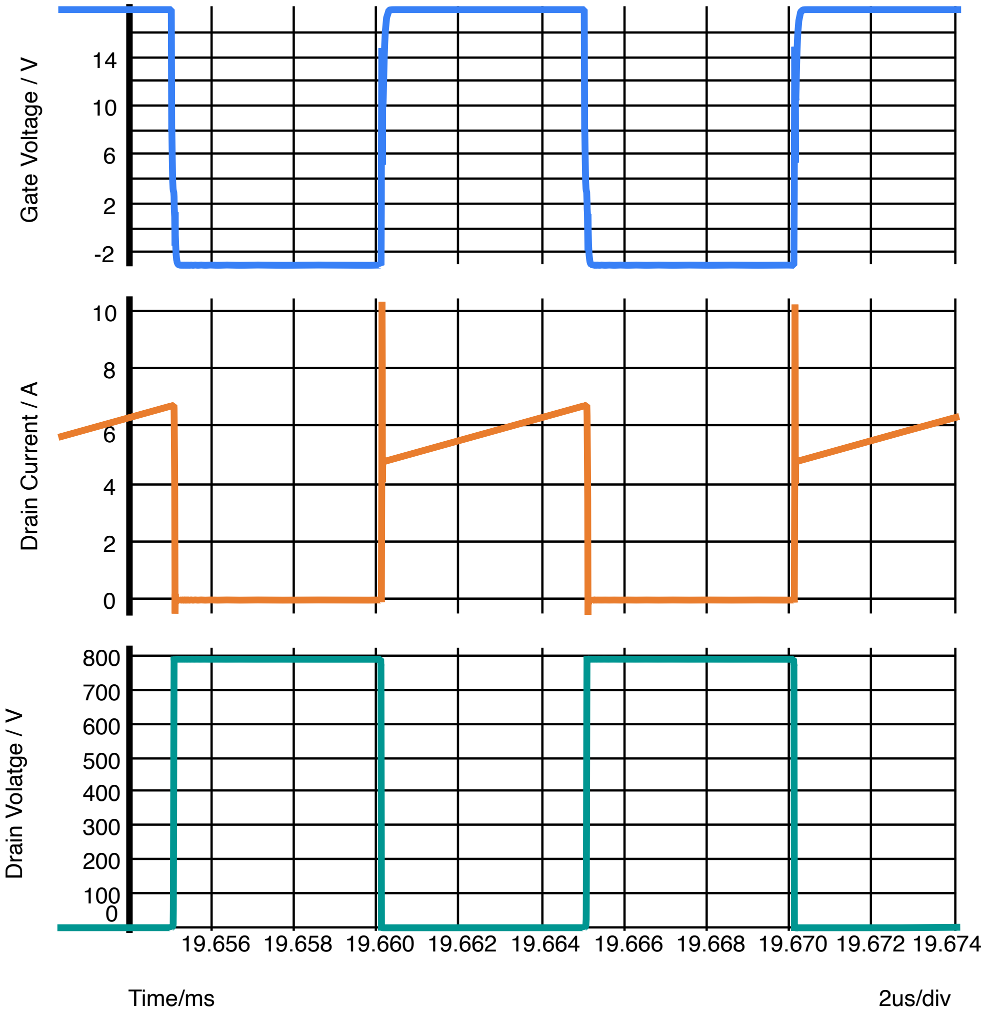
Boost Example

Boost example

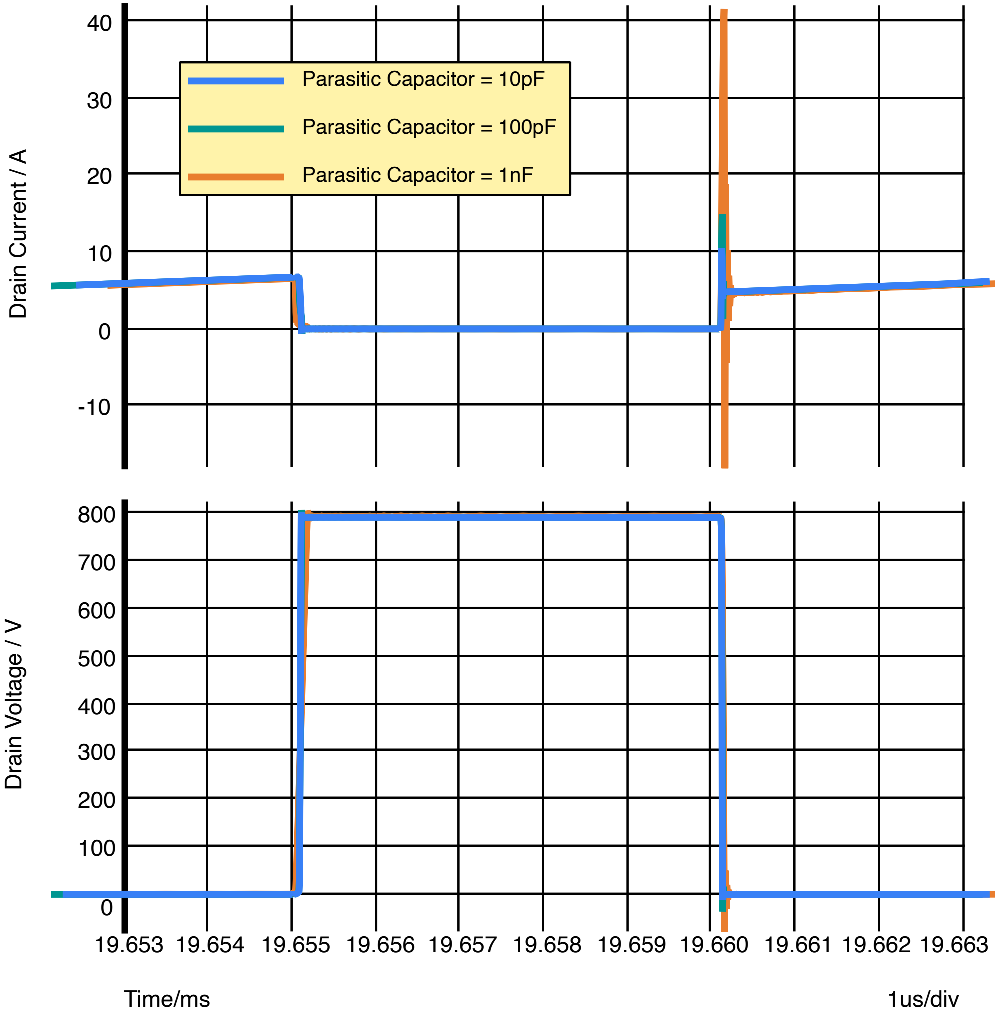
- Boost stage :

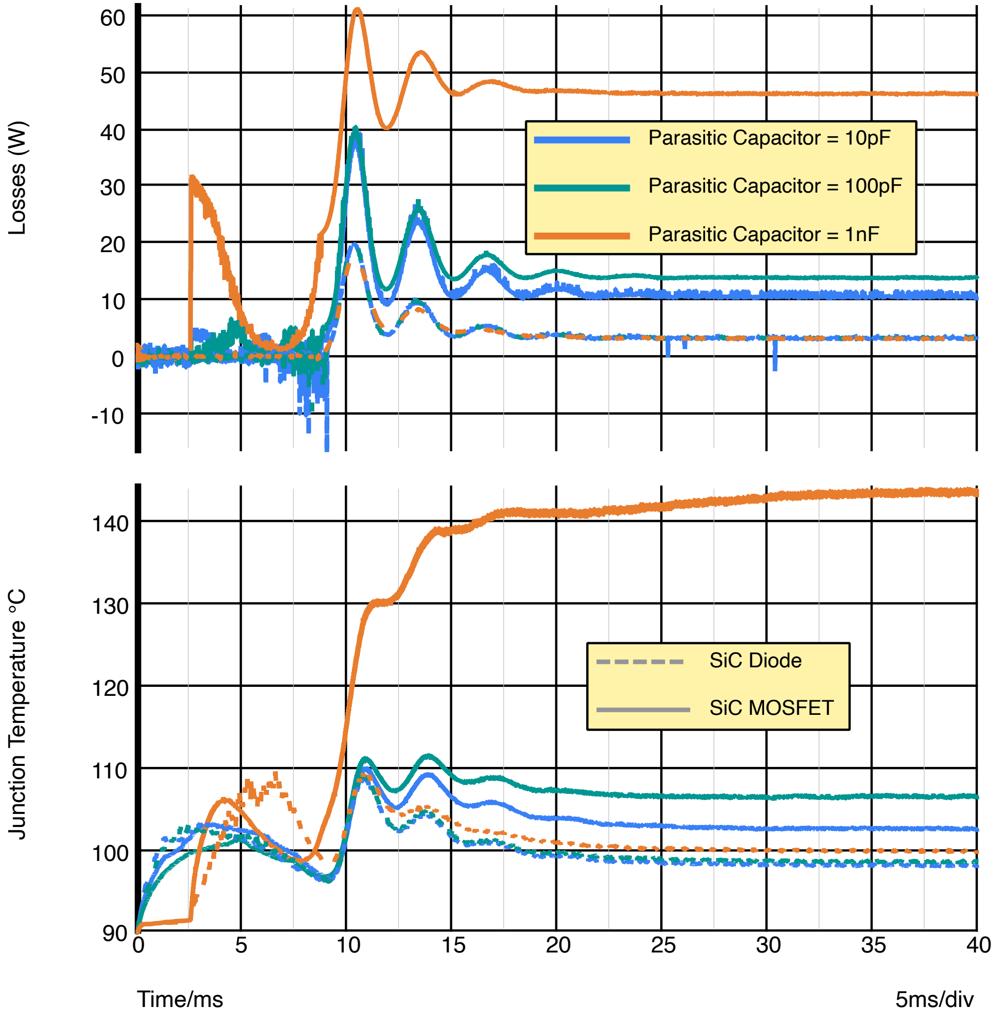


- Parameters :
  - Input : 400V
  - Output : 800V
  - Power : 2kW
  - Switching Frequency : 100kHz



Results with various inductor parasitics





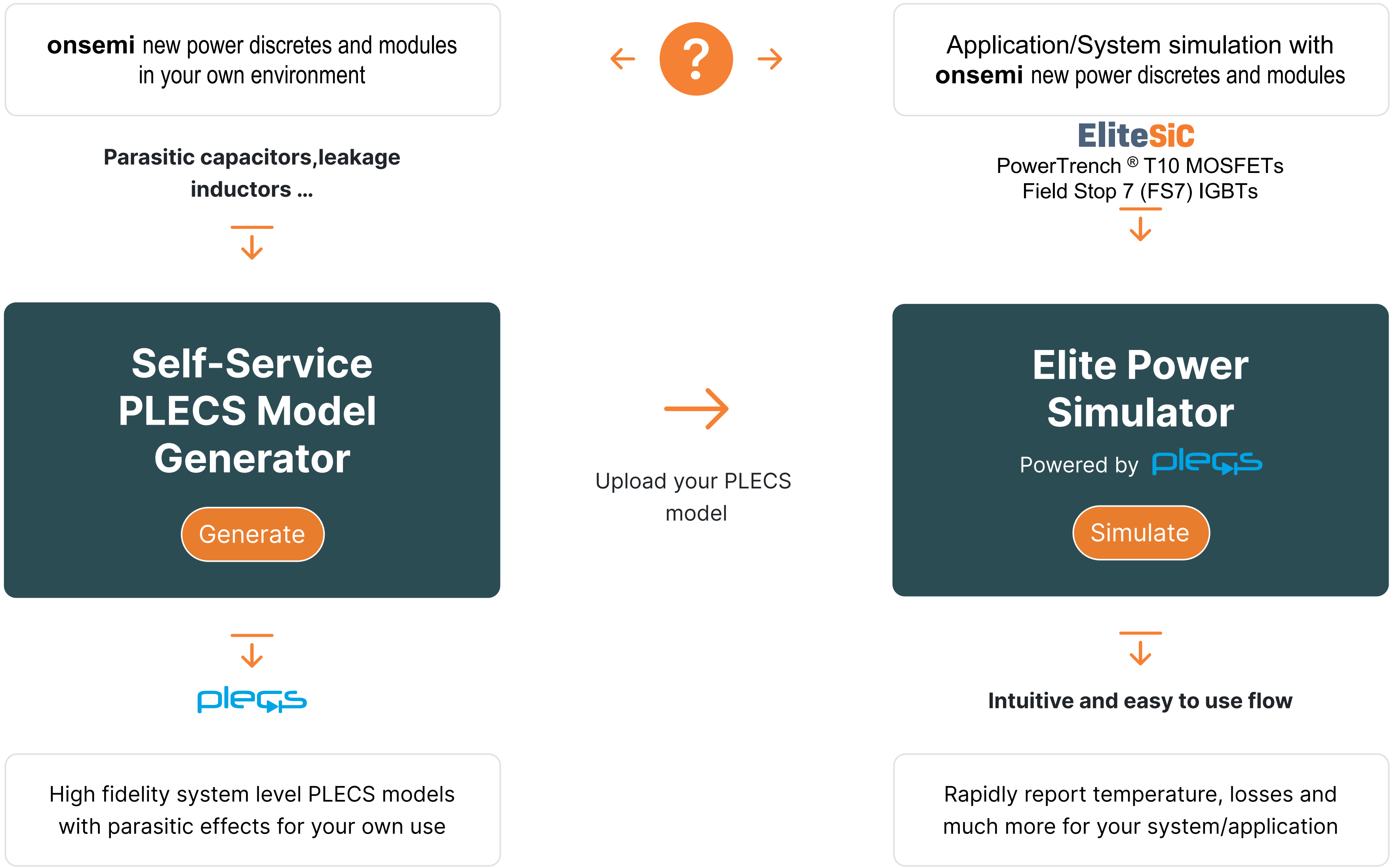
The parasitic inductor capacitor values are : 10pF, 100pF and 1nF.

The resonant frequencies associated are : 1.6MHz, 500kHz and 160kHz. The SiC Boost operates at 100kHz

onsemi online tool structure

2 in 1 !

New tool flow and interaction



onsemi new power discretes and modules in your own environment

?

Application/System simulation with **onsemi** new power discretes and modules

Parasitic capacitors,leakage inductors …

EliteSiC
PowerTrench ® T10 MOSFETs
Field Stop 7 (FS7) IGBTs

Self-Service PLECS Model Generator

Generate

Upload your PLECS model

Elite Power Simulator

Powered by plecs

Simulate

plecs

Intuitive and easy to use flow

High fidelity system level PLECS models with parasitic effects for your own use

Rapidly report temperature, losses and much more for your system/application

Mixing **onsemi** SPICE expertise and PLECS power

SPICE engine
to generate
PLECS models

With **onsemi**
Physical
&
Scalable
SPICE
Models

onsemi new power discretes and modules
in your own environment

**Parasitic capacitors,leakage
inductors …**

Self-Service PLECS Model Generator

Generate

PLECS

High fidelity system level PLECS models
with parasitic effects for your own use

?

Upload your PLECS
model

Application/System simulation with
onsemi new power discretes and modules

EliteSiC
PowerTrench ® T10 MOSFETs
Field Stop 7 (FS7) IGBTs

Elite Power Simulator

Powered by PLECS

Simulate

Intuitive and easy to use flow

Rapidly report temperature, losses and
much more for your system/application

PLECS engine
to generate
results

Why a plecs Model Generator ?

Self Service PLECS Model Generation (SSPMG)

Problem Statement:

- System level simulators like the industry standard tool PLECS require specific models for the power discretes or modules that are implemented in the simulation of various power converter topologies.
- The models consist of 3 major characteristics:
  - conduction losses,
  - switching energy losses,
  - and thermal impedance data.
- The loss data over bias and temperature is in a table which the system simulator interpolates based on the operation condition of the power device in the application.

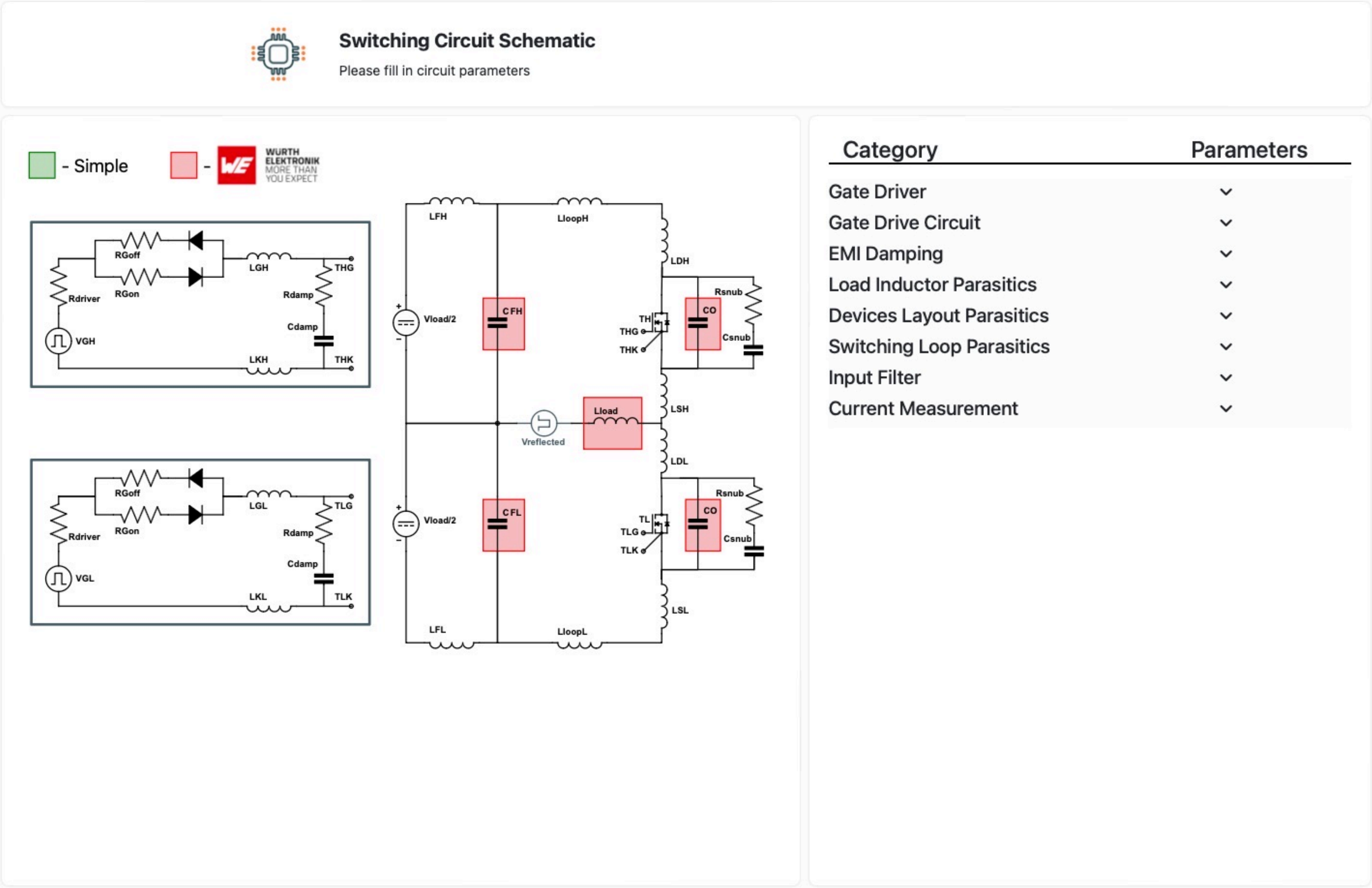
Self Service PLECS Model Generation (SSPMG)

Problem Statement:

- The models generally come from datasheets which presents 2 major problems:
  - The **switching loss data** are **dependent** on all **measurement setup parasitics** …
  - The datasheet data is limited and thus is often not dense enough to ensure accurate interpolation or extrapolation by the system level simulator.

- Models can also be obtained by measurement BUT, it is a time-consuming process
  - The switching loss data are dependent on all measurement setup parasitics …

Model Generator Schematic with Parasitics



Switching Circuit Schematic

Please fill in circuit parameters

🟩 - Simple 🟥 - WE WURTH ELEKTRONIK MORE THAN YOU EXPECT

Category	Parameters
Gate Driver	⌄
Gate Drive Circuit	⌄
EMI Damping	⌄
Load Inductor Parasitics	⌄
Devices Layout Parasitics	⌄
Switching Loop Parasitics	⌄
Input Filter	⌄
Current Measurement	⌄

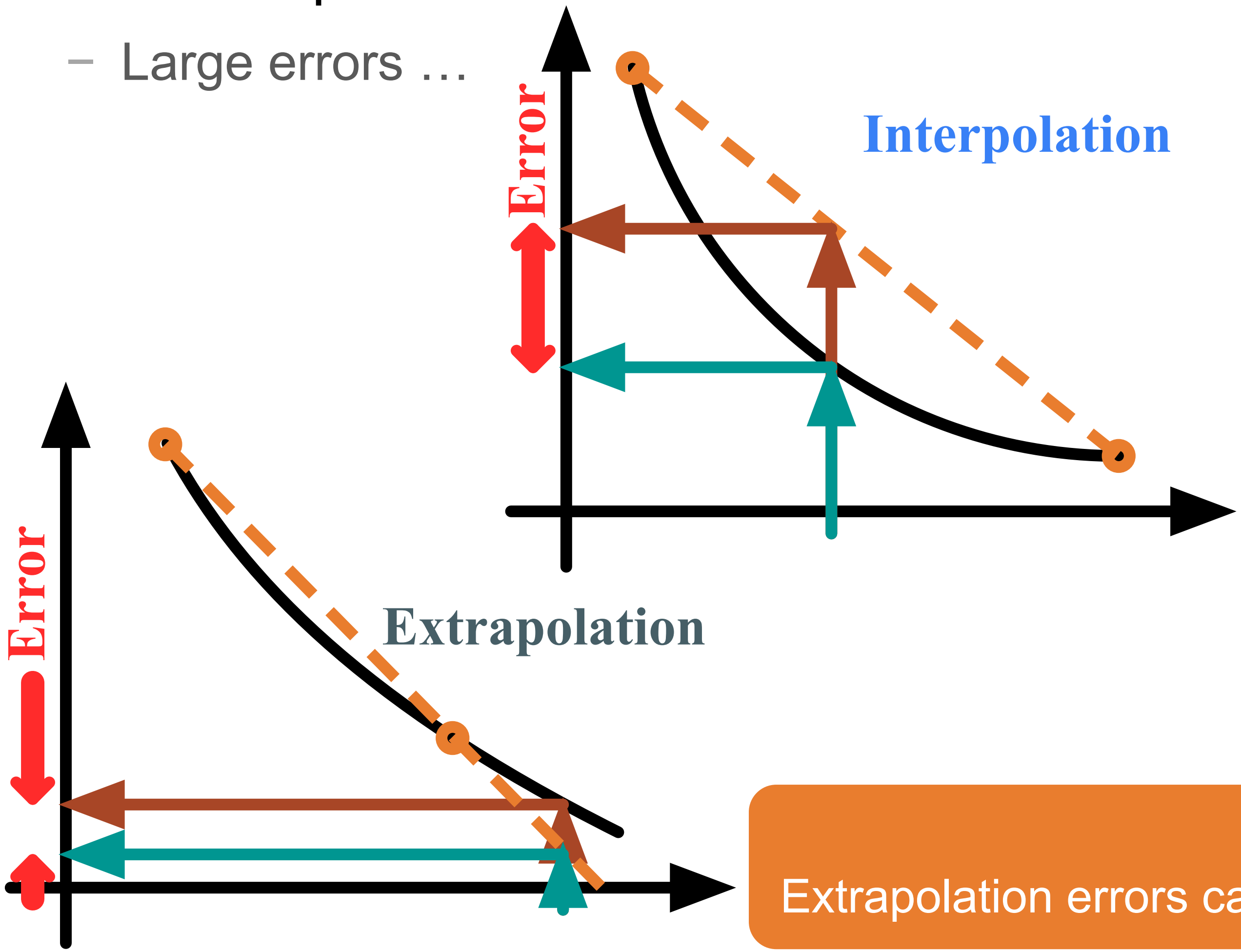
- The schematic includes :
  - Input decoupling with Capacitor ESR and ESL,
  - Loop PCB leakage inductors in the switching cell,
  - Drain and Source PCB leakage inductors and resistors,
  - Serie Resistor and Parallel Capacitor for the switching inductance,
  - Damping networks between Gate-Source and Drain-Source,
  - Gate drive network with split turn-on and turn-off resistors.

Data set density

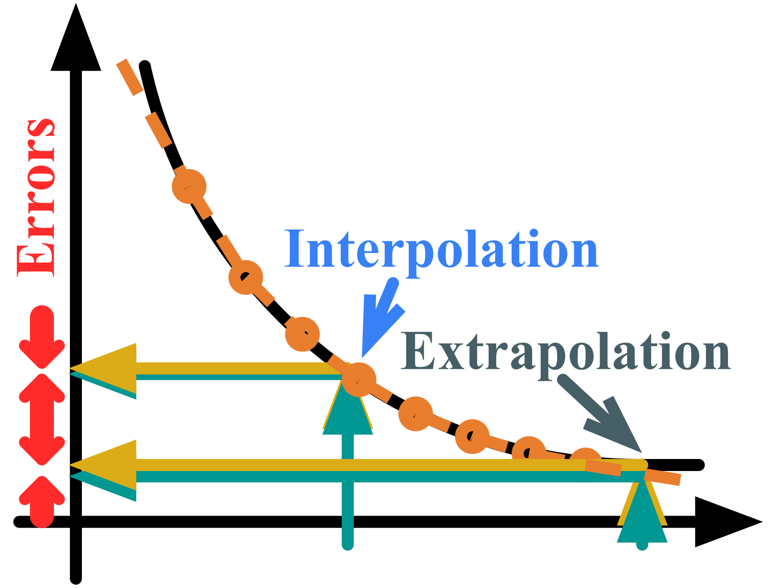
How it impacts results ?

Large Data Set for Interpolation and Extrapolation

- Few data points :
  - Large errors …



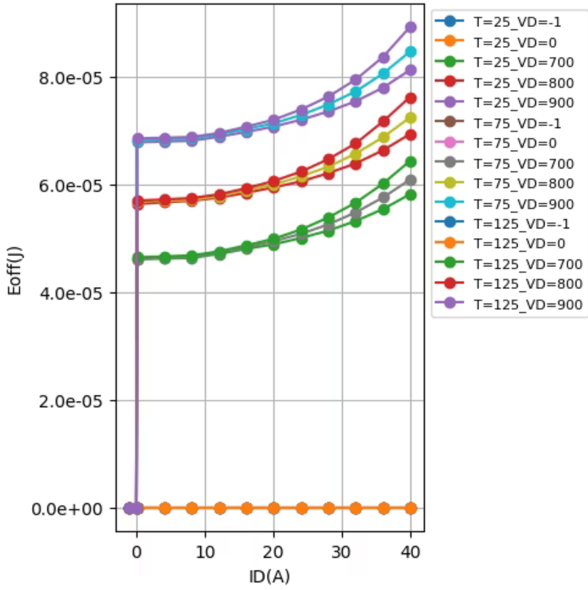
- Large Data Set :

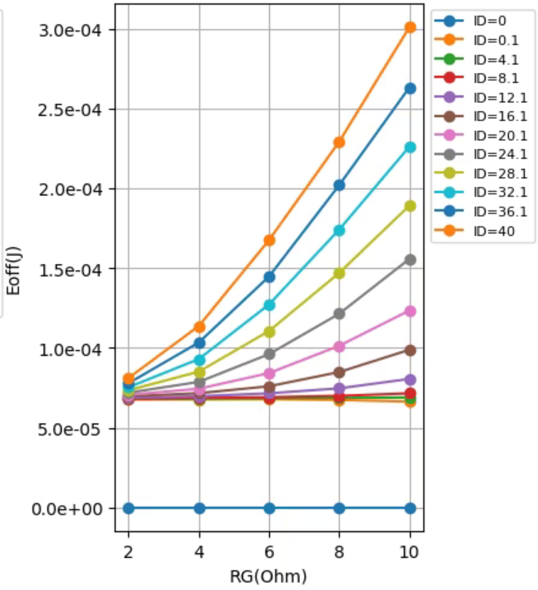


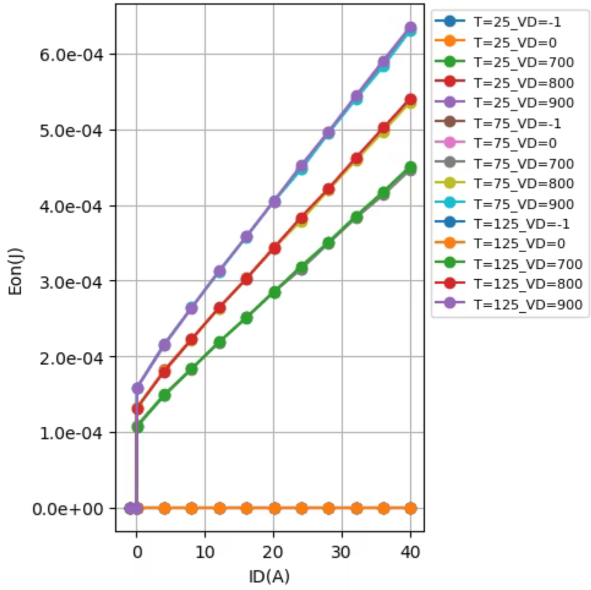
!!! Much smaller Errors !!!
Extrapolation errors can be completely removed by selecting a large range

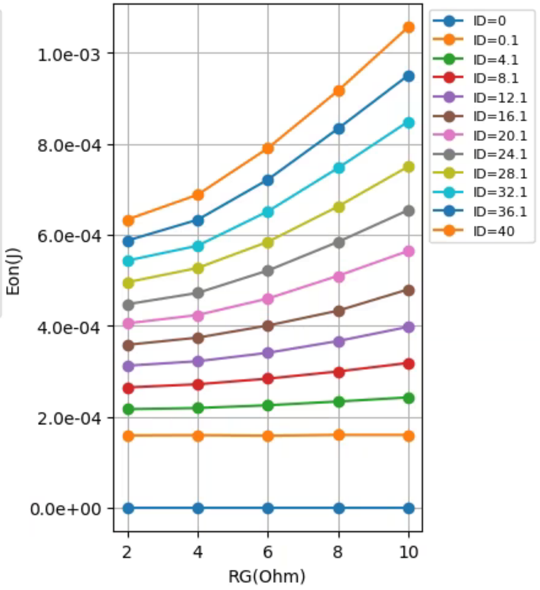
plecs modeling results

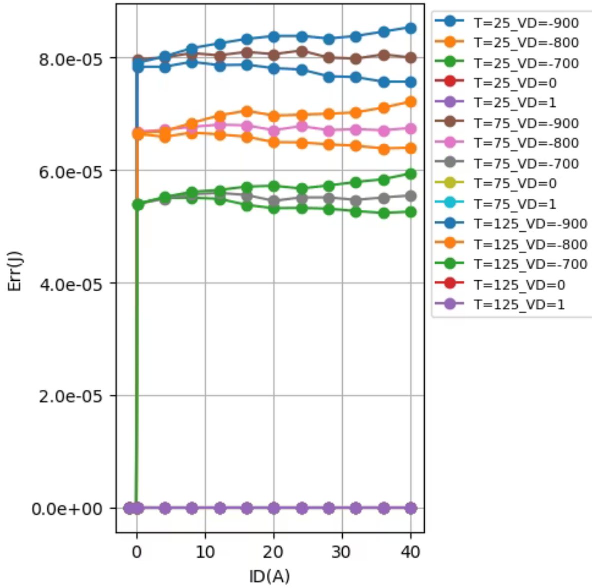
Self-Service PLECS Model : Double Pulse Tester Results

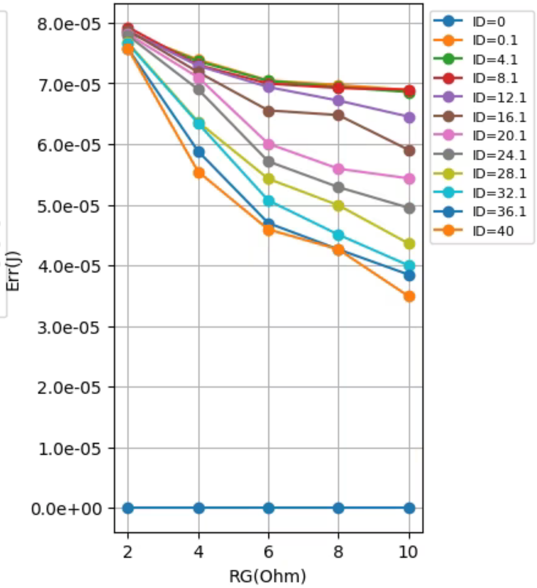


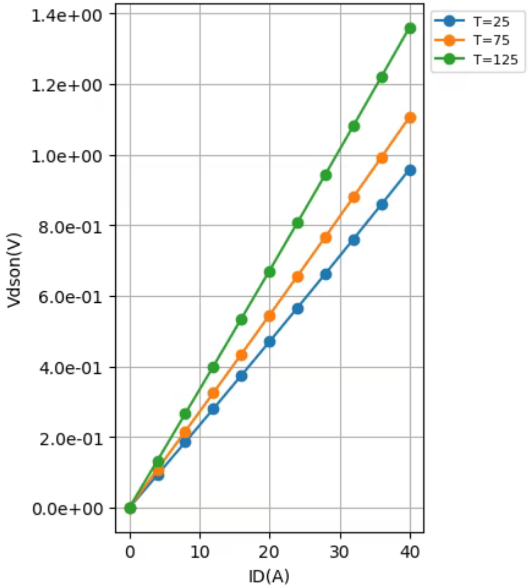


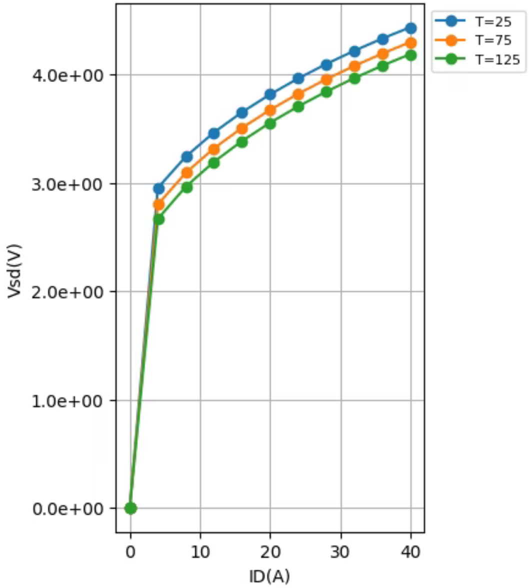










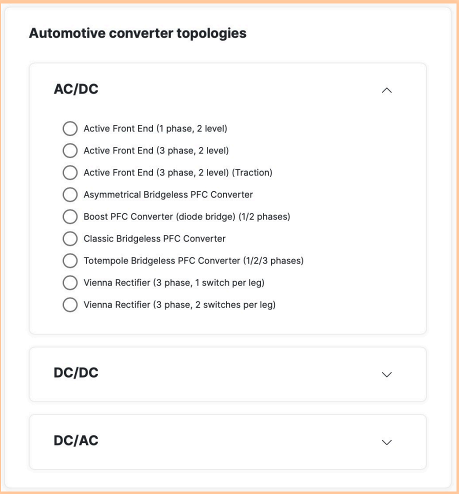


Elite Power Simulator

Topologies simulations

Online Simulator Topologies & Applications

All major topologies are available :



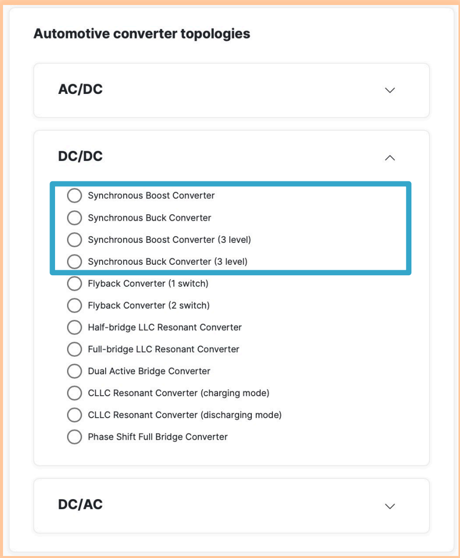
Automotive converter topologies

AC/DC

- ○ Active Front End (1 phase, 2 level)
- ○ Active Front End (3 phase, 2 level)
- ○ Active Front End (3 phase, 2 level) (Traction)
- ○ Asymmetrical Bridgeless PFC Converter
- ○ Boost PFC Converter (diode bridge) (1/2 phases)
- ○ Classic Bridgeless PFC Converter
- ○ Totempole Bridgeless PFC Converter (1/2/3 phases)
- ○ Vienna Rectifier (3 phase, 1 switch per leg)
- ○ Vienna Rectifier (3 phase, 2 switches per leg)

DC/DC

DC/AC



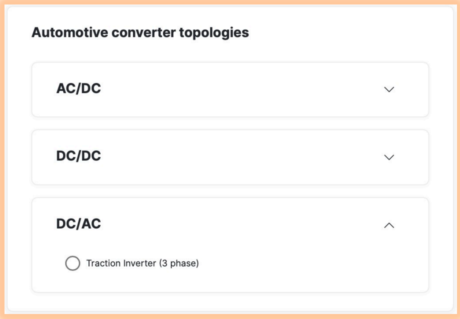
Automotive converter topologies

AC/DC

DC/DC

- ○ Synchronous Boost Converter
- ○ Synchronous Buck Converter
- ○ Synchronous Boost Converter (3 level)
- ○ Synchronous Buck Converter (3 level)
- ○ Flyback Converter (1 switch)
- ○ Flyback Converter (2 switch)
- ○ Half-bridge LLC Resonant Converter
- ○ Full-bridge LLC Resonant Converter
- ○ Dual Active Bridge Converter
- ○ CLLC Resonant Converter (charging mode)
- ○ CLLC Resonant Converter (discharging mode)
- ○ Phase Shift Full Bridge Converter

DC/AC



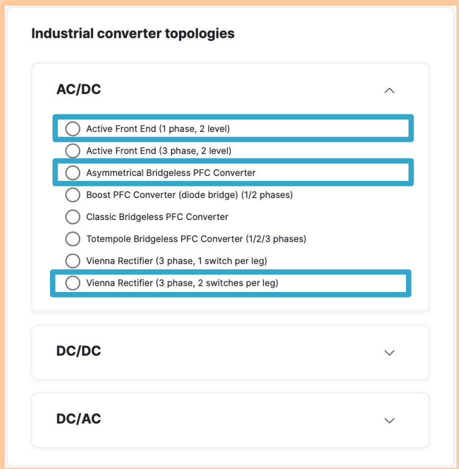
Automotive converter topologies

AC/DC

DC/DC

DC/AC

- ○ Traction Inverter (3 phase)



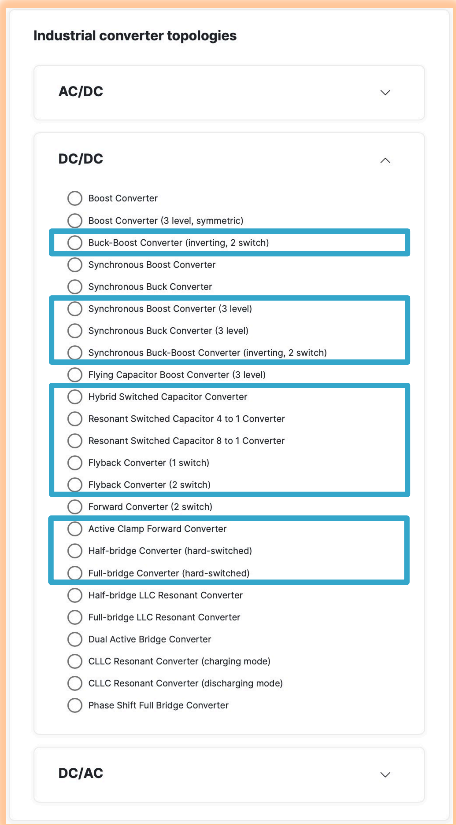
Industrial converter topologies

AC/DC

- ○ Active Front End (1 phase, 2 level)
- ○ Active Front End (3 phase, 2 level)
- ○ Asymmetrical Bridgeless PFC Converter
- ○ Boost PFC Converter (diode bridge) (1/2 phases)
- ○ Classic Bridgeless PFC Converter
- ○ Totempole Bridgeless PFC Converter (1/2/3 phases)
- ○ Vienna Rectifier (3 phase, 1 switch per leg)
- ○ Vienna Rectifier (3 phase, 2 switches per leg)

DC/DC

DC/AC



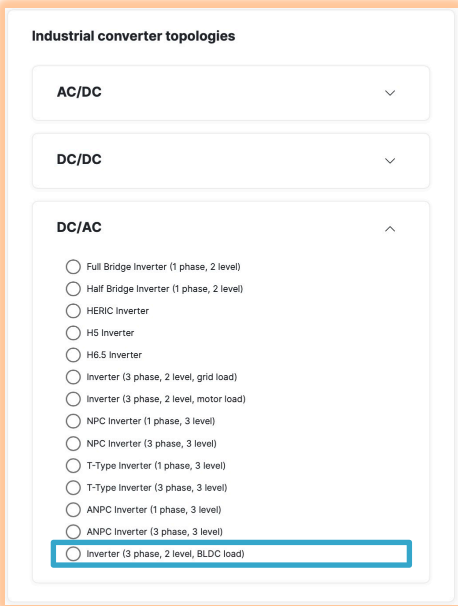
Industrial converter topologies

AC/DC

DC/DC

- ○ Boost Converter
- ○ Boost Converter (3 level, symmetric)
- ○ Buck-Boost Converter (inverting, 2 switch)
- ○ Synchronous Boost Converter
- ○ Synchronous Buck Converter
- ○ Synchronous Boost Converter (3 level)
- ○ Synchronous Buck Converter (3 level)
- ○ Synchronous Buck-Boost Converter (inverting, 2 switch)
- ○ Flying Capacitor Boost Converter (3 level)
- ○ Hybrid Switched Capacitor Converter
- ○ Resonant Switched Capacitor 4 to 1 Converter
- ○ Resonant Switched Capacitor 8 to 1 Converter
- ○ Flyback Converter (1 switch)
- ○ Flyback Converter (2 switch)
- ○ Forward Converter (2 switch)
- ○ Active Clamp Forward Converter
- ○ Half-bridge Converter (hard-switched)
- ○ Full-bridge Converter (hard-switched)
- ○ Half-bridge LLC Resonant Converter
- ○ Full-bridge LLC Resonant Converter
- ○ Dual Active Bridge Converter
- ○ CLLC Resonant Converter (charging mode)
- ○ CLLC Resonant Converter (discharging mode)
- ○ Phase Shift Full Bridge Converter

DC/AC



Industrial converter topologies

AC/DC

DC/DC

DC/AC

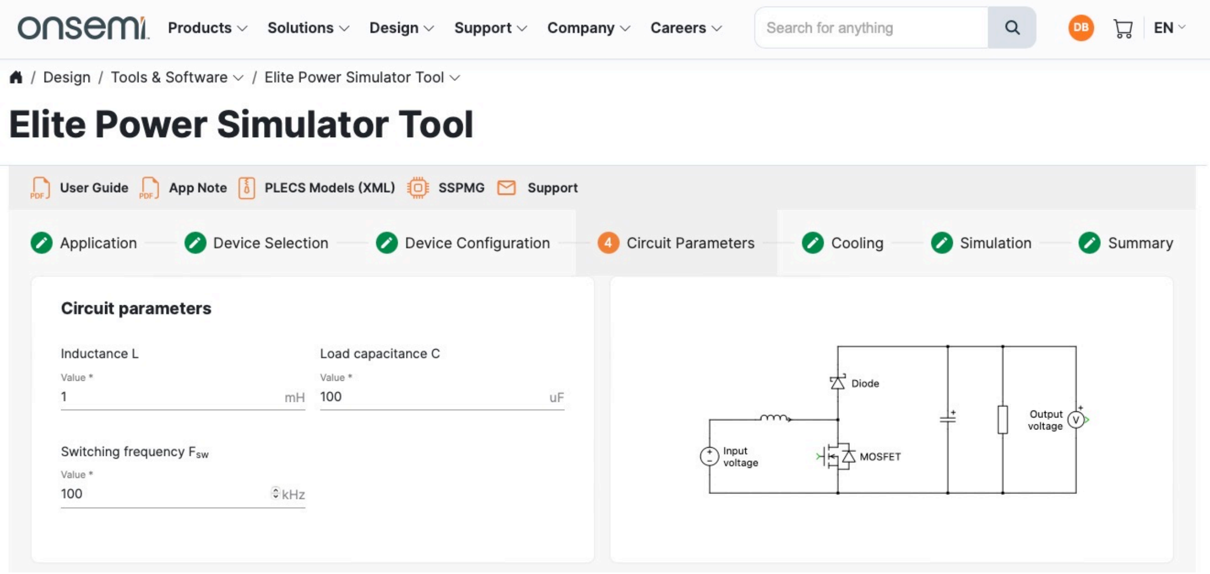
- ○ Full Bridge Inverter (1 phase, 2 level)
- ○ Half Bridge Inverter (1 phase, 2 level)
- ○ HERIC Inverter
- ○ H5 Inverter
- ○ H6.5 Inverter
- ○ Inverter (3 phase, 2 level, grid load)
- ○ Inverter (3 phase, 2 level, motor load)
- ○ NPC Inverter (1 phase, 3 level)
- ○ NPC Inverter (3 phase, 3 level)
- ○ T-Type Inverter (1 phase, 3 level)
- ○ T-Type Inverter (3 phase, 3 level)
- ○ ANPC Inverter (1 phase, 3 level)
- ○ ANPC Inverter (3 phase, 3 level)
- ○ Inverter (3 phase, 2 level, BLDC load)

New Topologies available with T10

onsemi.com products available are :

- All SiC MOSFET Discretes and Modules
- New Field Stop 7 IGBT Discretes and IPMs
- New T10 Low and Medium Voltage Silicon MOSFETs

Boost Example



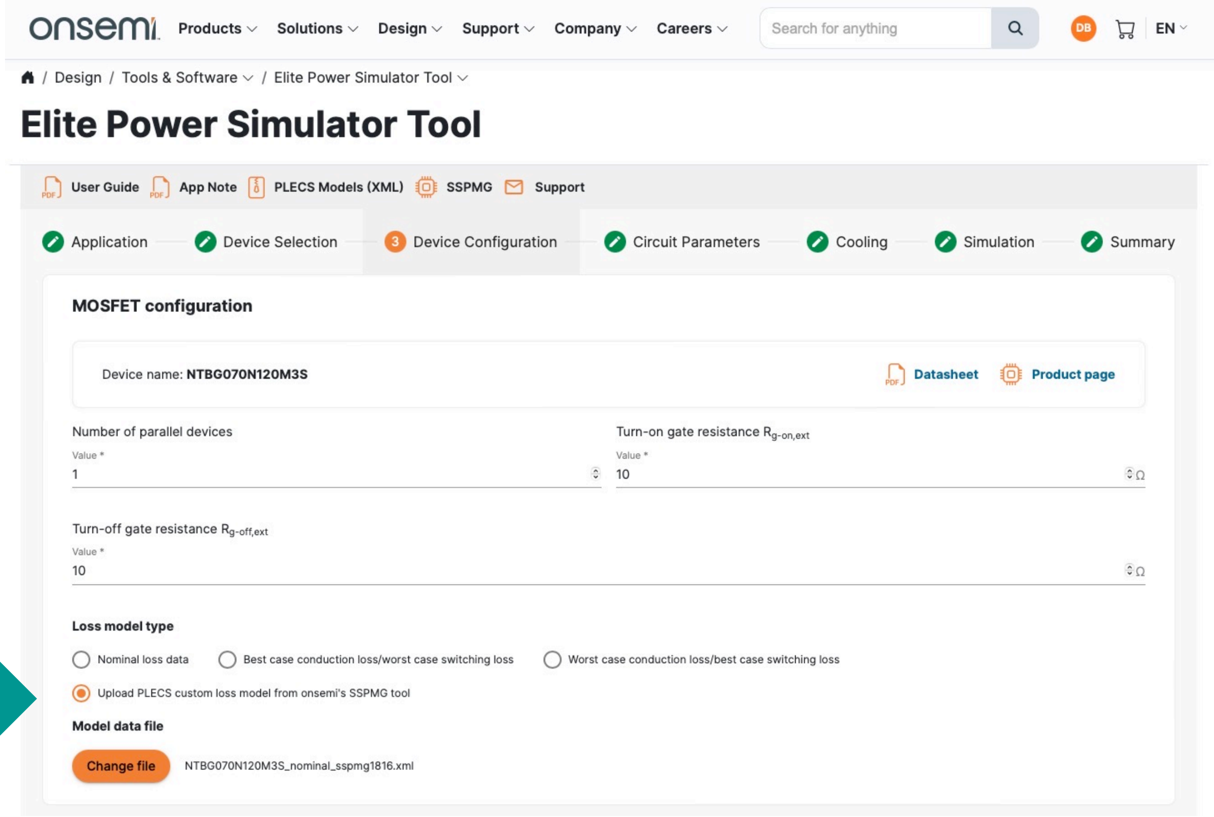
Elite Power Simulator Tool

Circuit parameters

Inductance L: Value * 1 mH

Load capacitance C: Value * 100 uF

Switching frequency F_{sw}: Value * 100 kHz



Elite Power Simulator Tool

MOSFET configuration

Device name: **NTBG070N120M3S**

Number of parallel devices: Value * 1

Turn-on gate resistance $R_{g\text{-on,ext}}$: Value * 10 Ω

Turn-off gate resistance $R_{g\text{-off,ext}}$: Value * 10 Ω

Loss model type

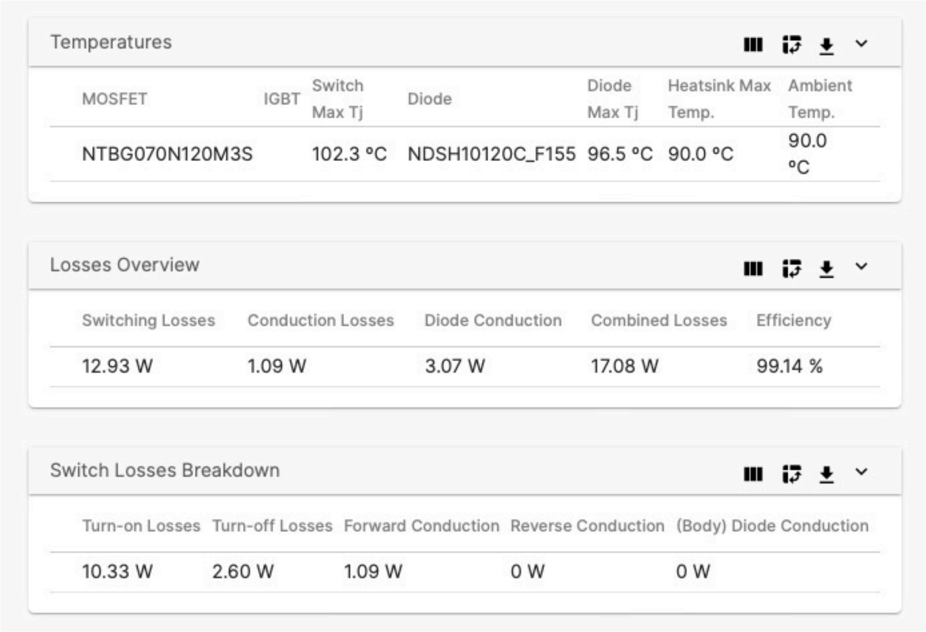
○ Nominal loss data
○ Best case conduction loss/worst case switching loss
○ Worst case conduction loss/best case switching loss
● Upload PLECS custom loss model from onsemi's SSPMG tool

Model data file

NTBG070N120M3S_nominal_sspmg1816.xml

Using model generated with parasistics

Results with nominal model



Temperatures

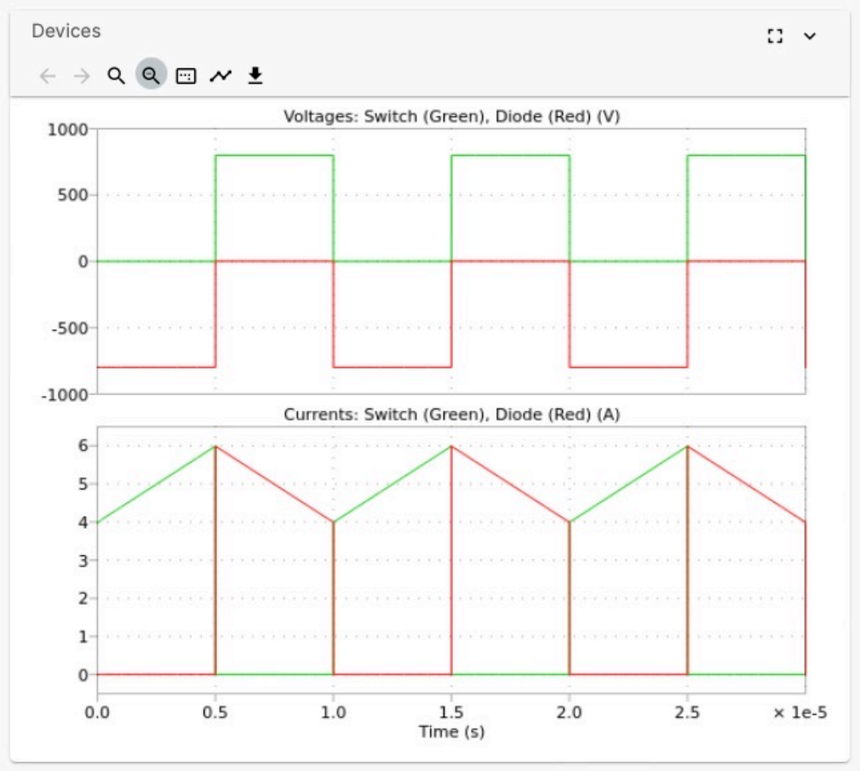
MOSFET	IGBT	Switch Max Tj	Diode	Diode Max Tj	Heatsink Max Temp.	Ambient Temp.
NTBG070N120M3S		102.3 °C	NDSH10120C_F155	96.5 °C	90.0 °C	90.0 °C

Losses Overview

Switching Losses	Conduction Losses	Diode Conduction	Combined Losses	Efficiency
12.93 W	1.09 W	3.07 W	17.08 W	99.14 %

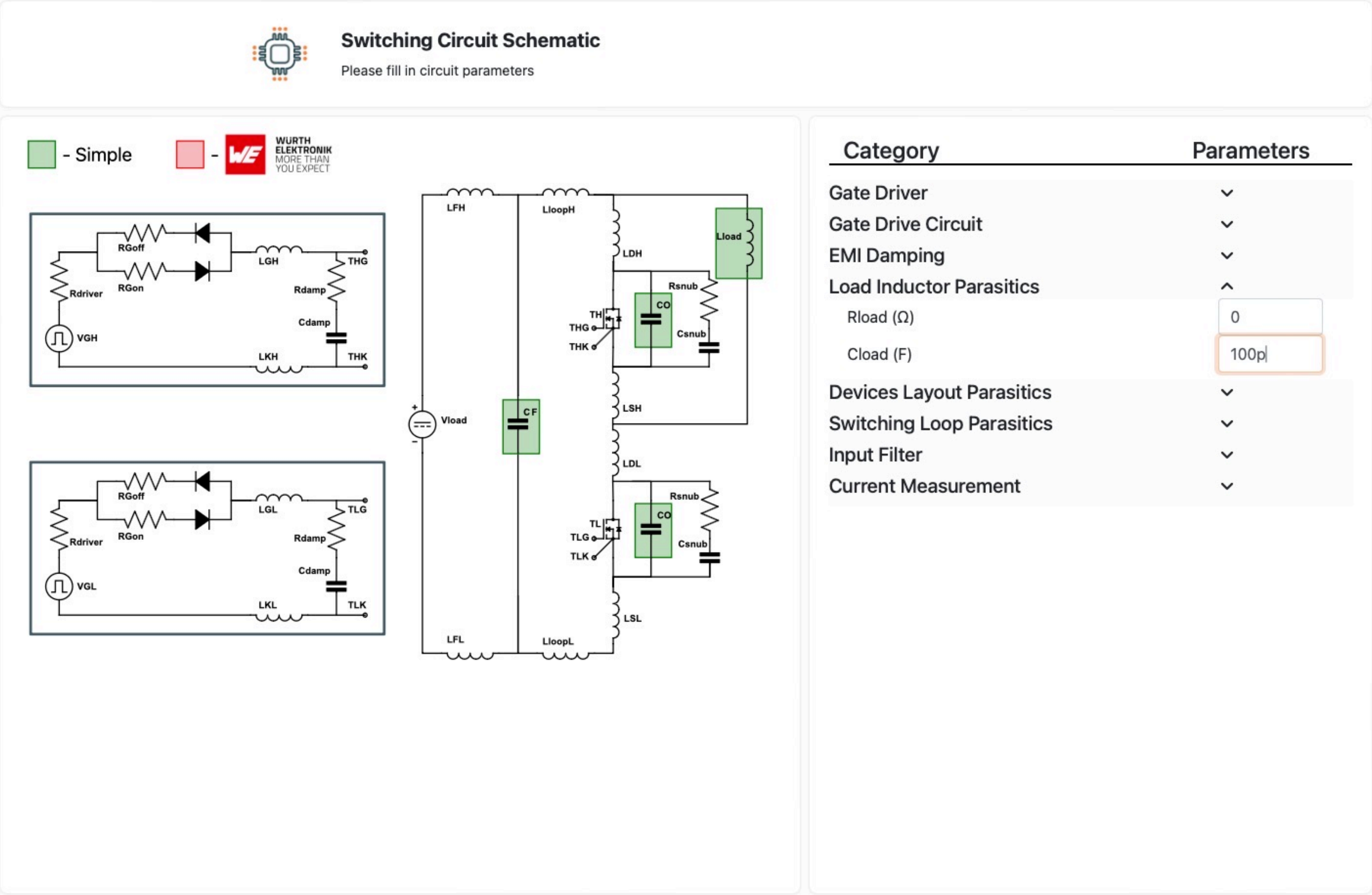
Switch Losses Breakdown

Turn-on Losses	Turn-off Losses	Forward Conduction	Reverse Conduction	(Body) Diode Conduction
10.33 W	2.60 W	1.09 W	0 W	0 W



Results with various inductor parasitic capacitors

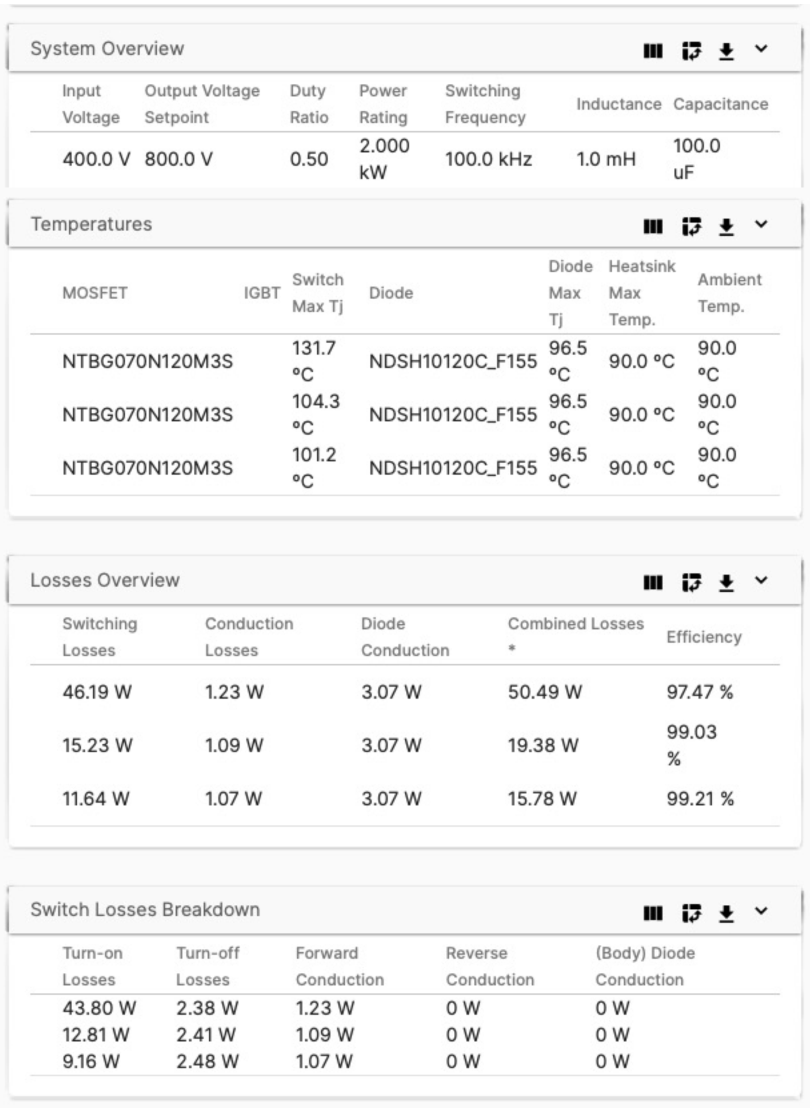
Generating models for 10pF, 100pF, 1nF capacitors



Switching Circuit Schematic

Please fill in circuit parameters

Category	Parameters
Gate Driver	⌄
Gate Drive Circuit	⌄
EMI Damping	⌄
Load Inductor Parasitics	⌃
Rload (Ω)	0
Cload (F)	100p
Devices Layout Parasitics	⌄
Switching Loop Parasitics	⌄
Input Filter	⌄
Current Measurement	⌄



System Overview

Input Voltage	Output Voltage Setpoint	Duty Ratio	Power Rating	Switching Frequency	Inductance	Capacitance
400.0 V	800.0 V	0.50	2.000 kW	100.0 kHz	1.0 mH	100.0 uF

Temperatures

MOSFET	IGBT	Switch Max Tj	Diode	Diode Max Tj	Heatsink Max Temp.	Ambient Temp.
NTBG070N120M3S		131.7 °C	NDSH10120C_F155	96.5 °C	90.0 °C	90.0 °C
NTBG070N120M3S		104.3 °C	NDSH10120C_F155	96.5 °C	90.0 °C	90.0 °C
NTBG070N120M3S		101.2 °C	NDSH10120C_F155	96.5 °C	90.0 °C	90.0 °C

Losses Overview

Switching Losses	Conduction Losses	Diode Conduction	Combined Losses *	Efficiency
46.19 W	1.23 W	3.07 W	50.49 W	97.47 %
15.23 W	1.09 W	3.07 W	19.38 W	99.03 %
11.64 W	1.07 W	3.07 W	15.78 W	99.21 %

Switch Losses Breakdown

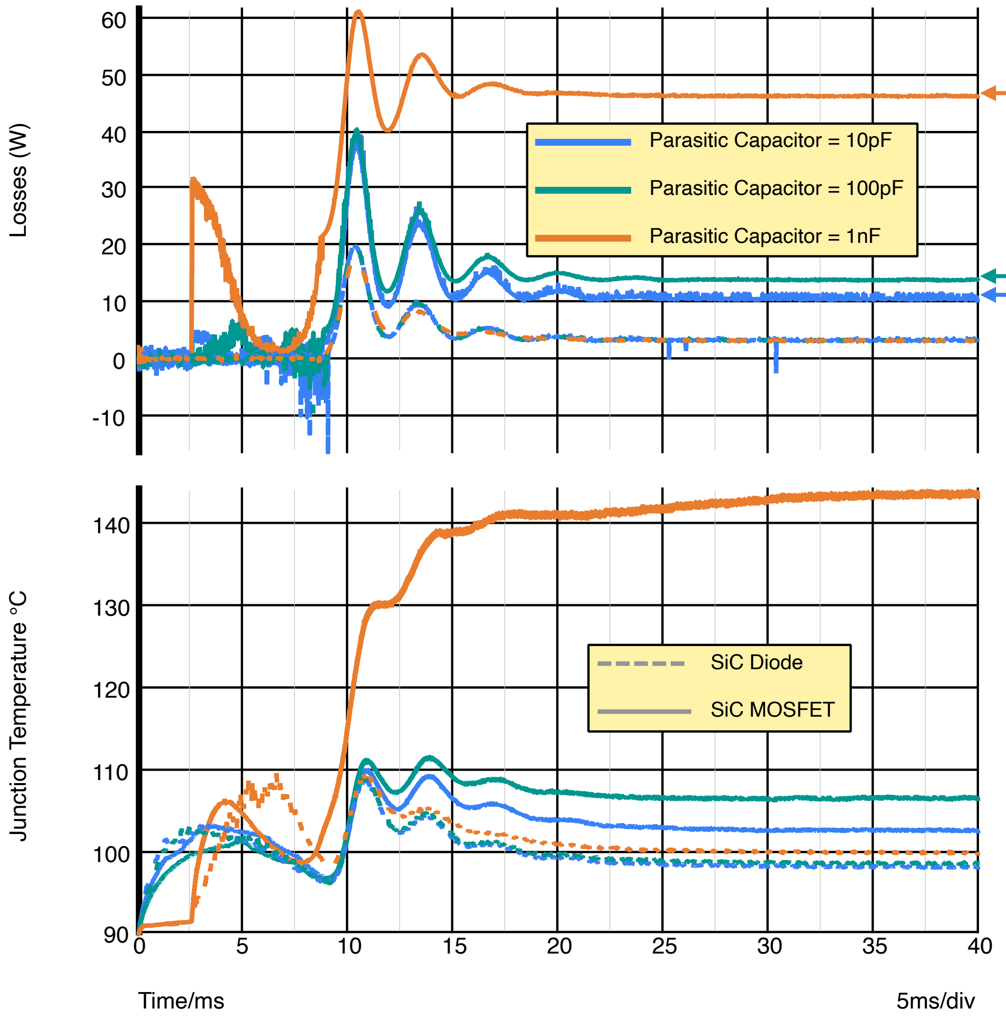
Turn-on Losses	Turn-off Losses	Forward Conduction	Reverse Conduction	(Body) Diode Conduction
43.80 W	2.38 W	1.23 W	0 W	0 W
12.81 W	2.41 W	1.09 W	0 W	0 W
9.16 W	2.48 W	1.07 W	0 W	0 W

Comparing results

SPICE vs Custom plecs models

Results with various inductor parasitic capacitors

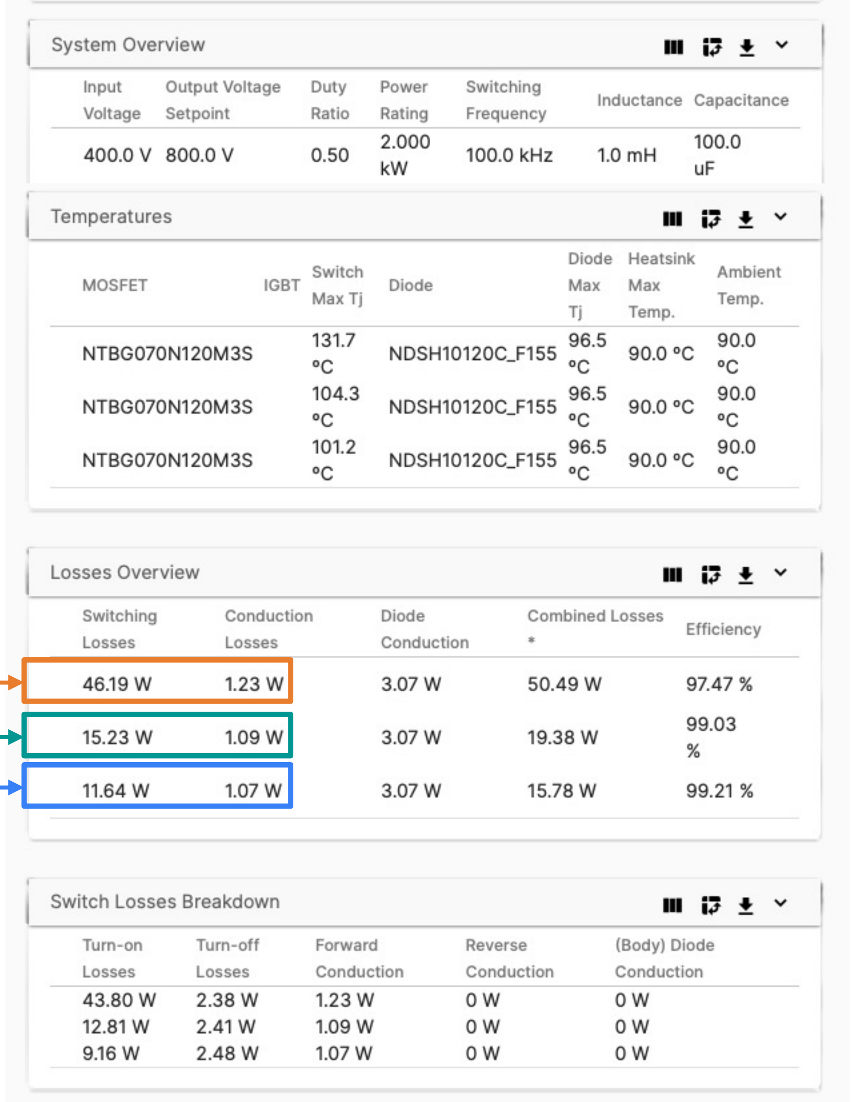
Generated models for 10pF, 100pF, 1nF capacitors



~47W

~16W

~12W



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Conclusions

Conclusion

- **onsemi** has developed new SPICE modeling technic to face new SiC material challenges and gave designers a better understanding of dynamic behaviors.

- **onsemi** brings a new online platform based on plecs with unique feature :
  Self Service plecs Model Generation (SSPMG)
  companion of the Elite Power Simulator for systems' simulations.
  - Using on **onsemi** **high accuracy Physical & Scalable SPICE models**
  - With larger tables for better interpolations and NO extrapolations

- The focus of **onsemi** SPICE models and online tools are **Accuracy** and not give unreachable results…and unexpected hope.

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Physical & Scalable Modeling IEEE Papers

- [1] A Physically Based Scalable SPICE Model for Silicon Carbide Power MOSFETs
  https://ieeexplore.ieee.org/document/7931077/
- [2] SiC MOSFET Corner and Statistical SPICE Model Generation
  https://ieeexplore.ieee.org/document/9170091/
- [3] A physically based scalable SPICE model for Shielded-Gate Trench Power MOSFETs
  https://ieeexplore.ieee.org/document/7520817/

Physical & Scalable Modeling help available at onsemi.com

- [1] An Introduction to Physical Scalable Models for Wide Bandgap Power Semiconductor – Part One (Blog article)
  https://www.onsemi.com/blog/industrial-cloud-power/wide-band-gap-ecosystem-part-i
- [2] Wide Bandgap Power Semiconductor: Silicon Carbide MOSFET Models – Part Two – (Blog Article)
  https://www.onsemi.com/blog/industrial-cloud-power/wide-band-gap-ecosystem-switches-disruptive-environments
- [3] Wide Bandgap Semiconductor Simulation Model Verification – Part Three – (Blog Article)
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- [4] Physically Based, Scalable SPICE Modeling Methodologies for Modern Power Electronic Devices – (White paper)
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- [7] How to use Physical and Scalable Models with SIMetrix, OrCAD and LTSpice – (Application note)
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  https://www.onsemi.com/pub/collateral/tnd6395-d.pdf
- [14] SiC Simulation – (Tutorial)
  https://www.onsemi.com/pub/collateral/tnd6421-d.pdf