ETH zürich

Power Electronic Systems Laboratory

Accurate Calorimetric Switching Loss Measurement of Ultra-Fast Power Semiconductors

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EMC in Power Electronics: From Harmonics to MHz – Design for EMC and Fast Switching

4th May 2017

Accurate Calorimetric Switching Loss Measurement of Ultra-Fast Power Semiconductors

M. Guacci, D. Neumayr, D. Rothmund, J. Azurza A., D. Bortis, and **J.W. Kolar**

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Outline

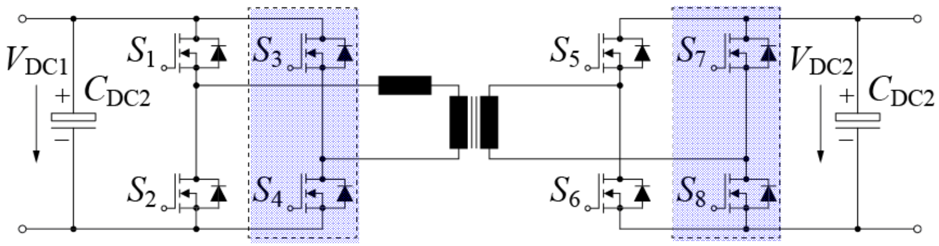
- ► Impact of Switching Loss
- ► Electric Measurement
- ► Accurate Calorimetric Method
- ► Conclusion - Outlook

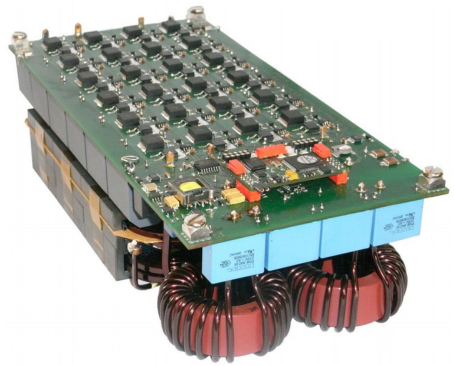
Impact of Switching Loss

Bridge Leg
Soft-Switching Operation
Impact on Efficiency and Volume

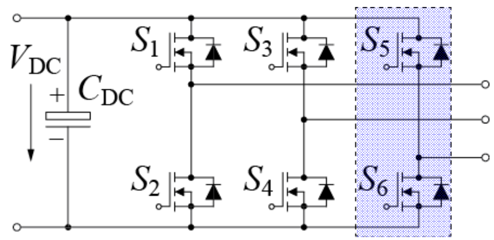
Switching Loss – Bridge Leg

Dual Active Bridge

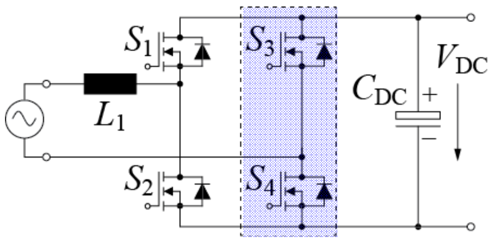


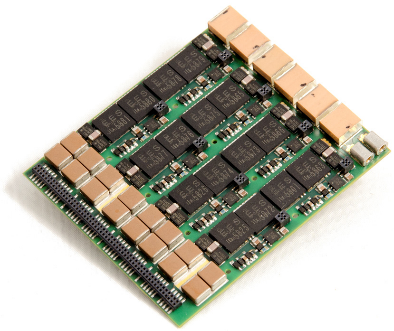


3-Phase Inverter



PFC Rectifier





- > 1 Bridge Leg per Switching Power Converter
- Switching → Loss, Volume, Cost, ...

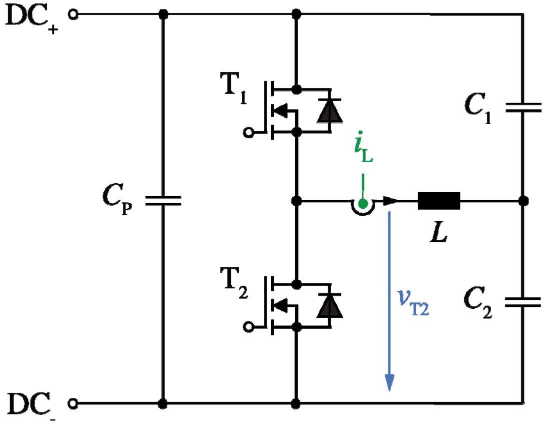
Switching Loss – Reduction

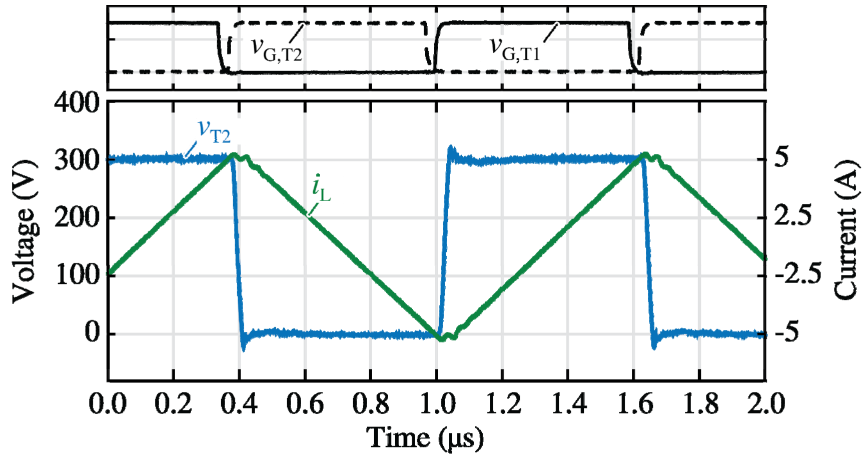
▶ Soft Zero Voltage Switching Operation (ZVS)

"…the load current has the direction of the anti-parallel diode of the turning on MOSFET…"
"…E_{oss} is exchanged between the load and the converter every switching cycle…"

▶ Example

Inductor Current
Switched Voltage





Switching Loss – Reduction

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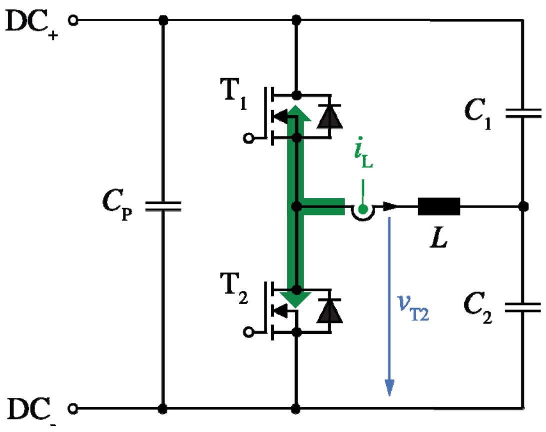

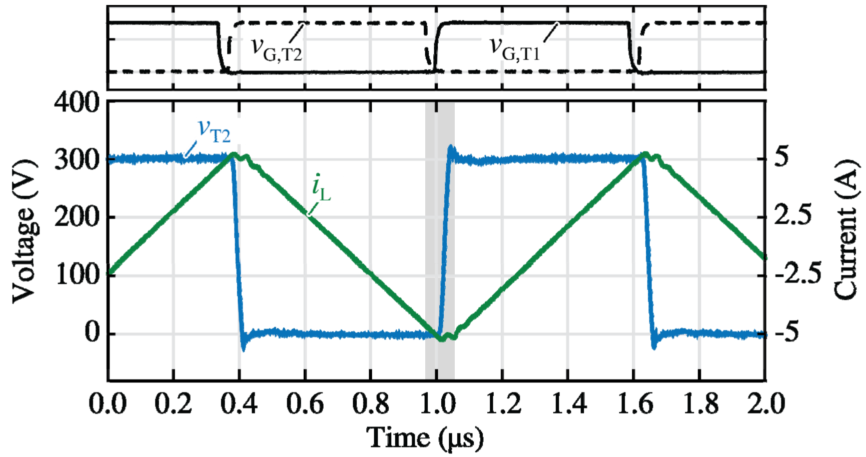

Switching Loss – Reduction

- **Soft Zero Voltage Switching Operation (ZVS)**

"...the load current has the direction of the anti-parallel diode of the turning on MOSFET..."
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- **Example**

Inductor Current
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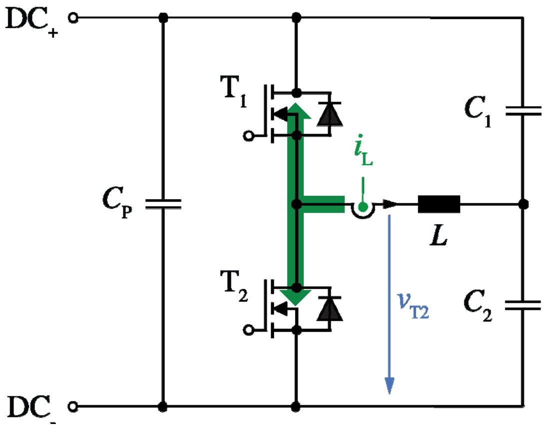
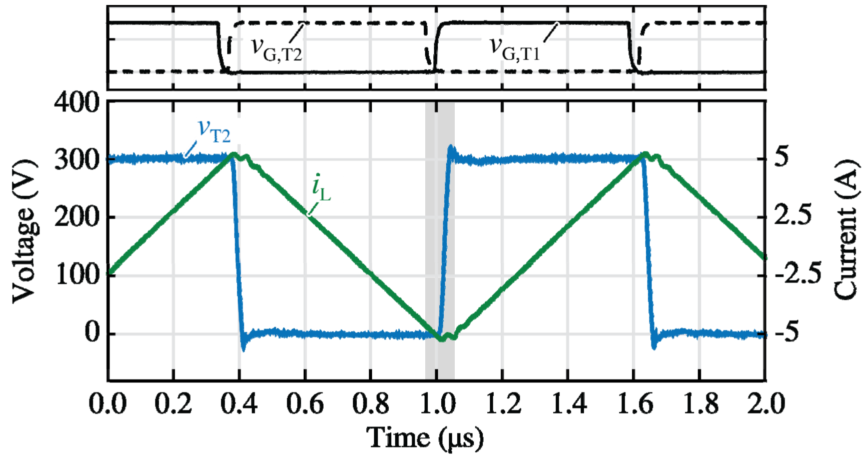




- **90% Switching Loss Reduction compared to Hard-Switching**
- **Enough?**

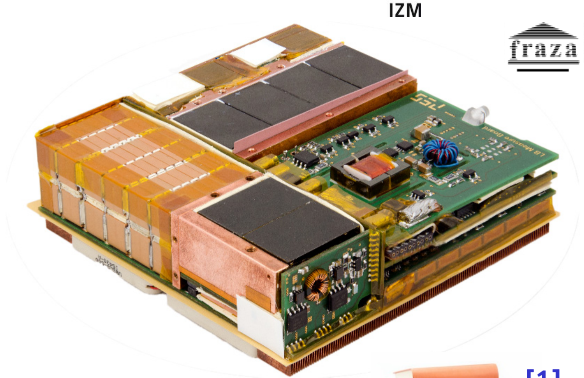
Soft-Switching Loss – Impact

- **The Google Little Box Challenge**

Build the 2kW Inverter with the Highest Power Density in the World

Fraunhofer IZM

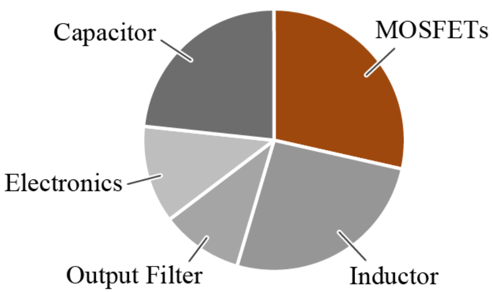
fraza



- **Bridge Leg**

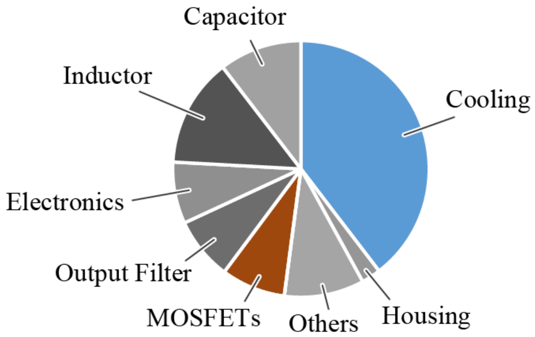
30%	Losses	22.3W	96.3% @ 2kW
22%	Volume	$53cm^3$	$8.2kW/cm^3$

- **Losses Pie**



Total Losses: 74.4W

- **Volume Pie**



Total Volume: $240.4cm^3$

[1]

$V_{Cooling} > 90cm^3$

$= k\, P_{loss}\, CSPI^{-1}$

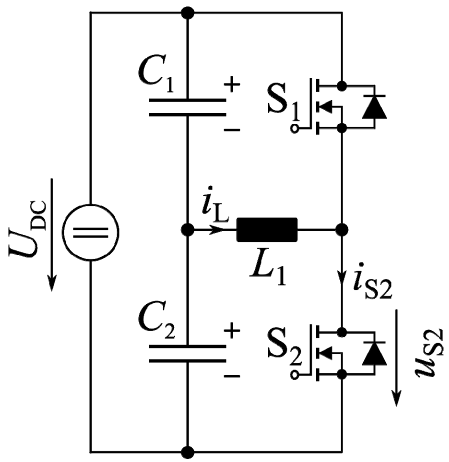
Electric Measurement

Double Pulse Test Method
Hard vs. Soft-Switching
Accuracy – Source of Error

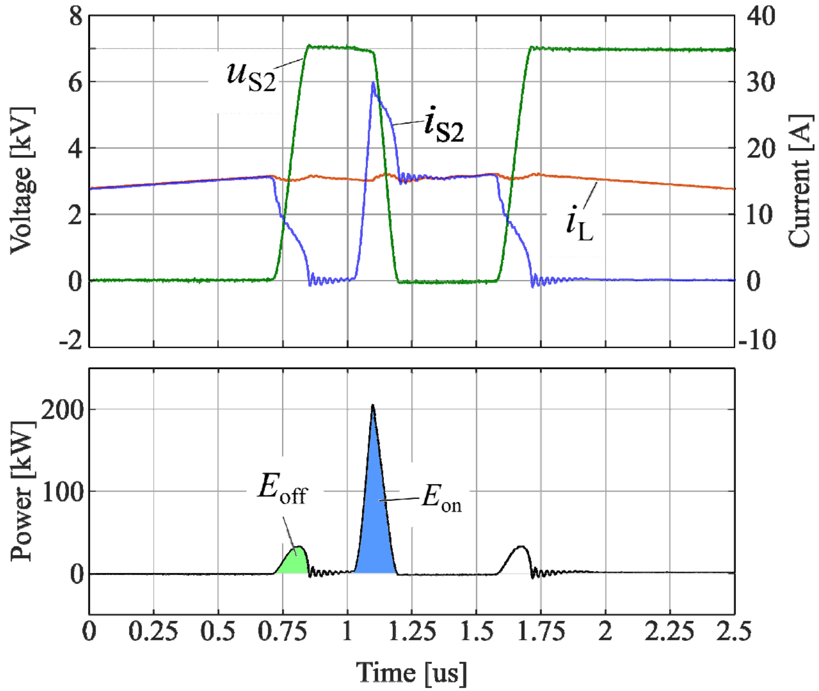
Electric Measurement

▶ Double Pulse Test (DPT)

Bridge Leg with Inductive Load



▶ Hard-Switching



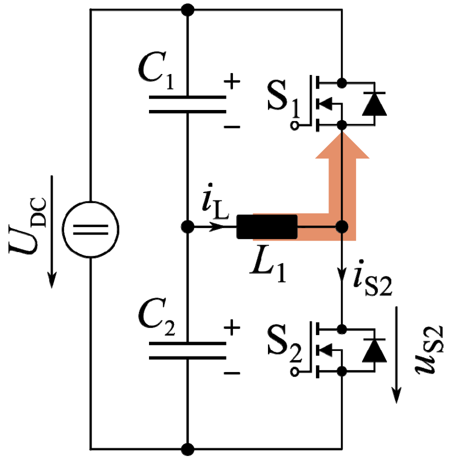
Switched Voltage
Inductor Current
Switched Current

[2]

Electric Measurement

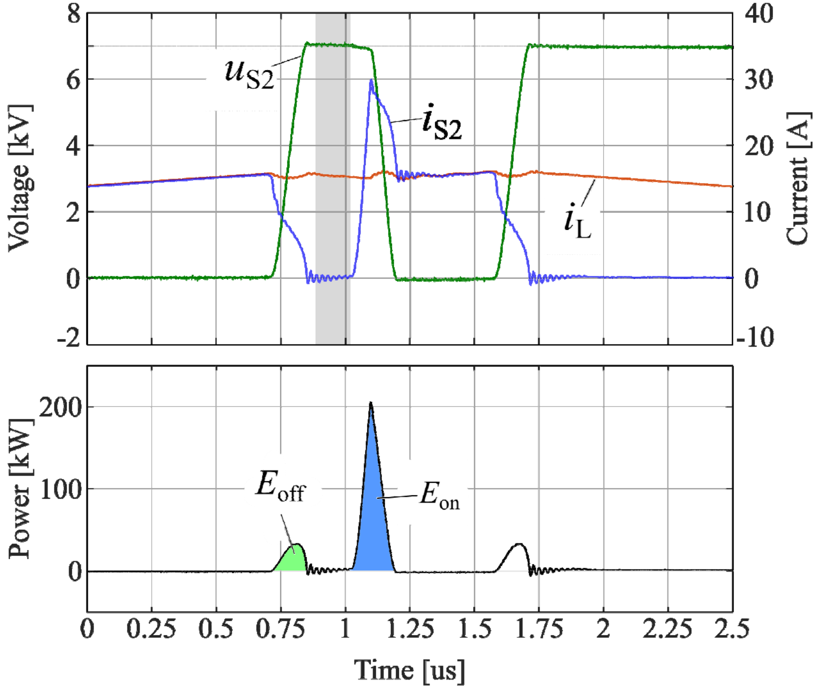
▶ Double Pulse Test (DPT)

Bridge Leg with Inductive Load



Hard Turn-On Transition

▶ Hard-Switching

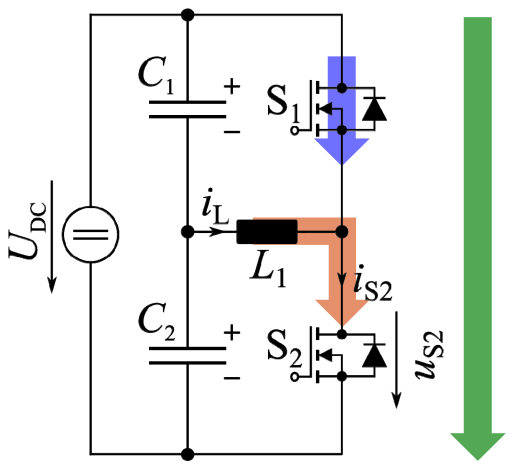


Switched Voltage
Inductor Current
Switched Current

Electric Measurement

▶ Double Pulse Test (DPT)

Bridge Leg with Inductive Load



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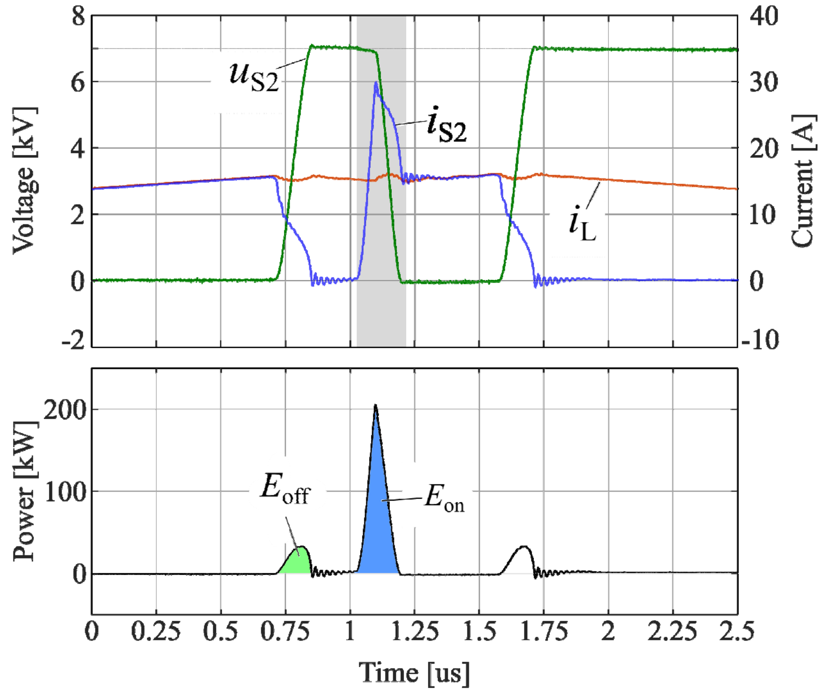

Switched Voltage
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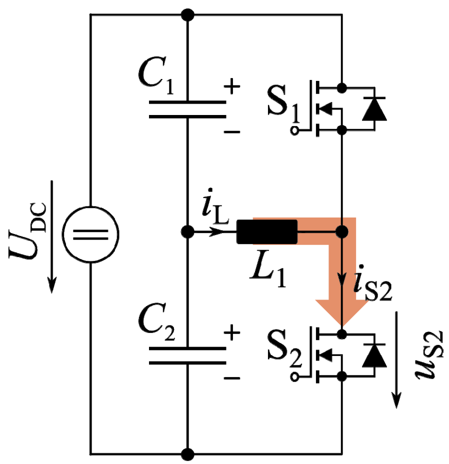
Electric Measurement

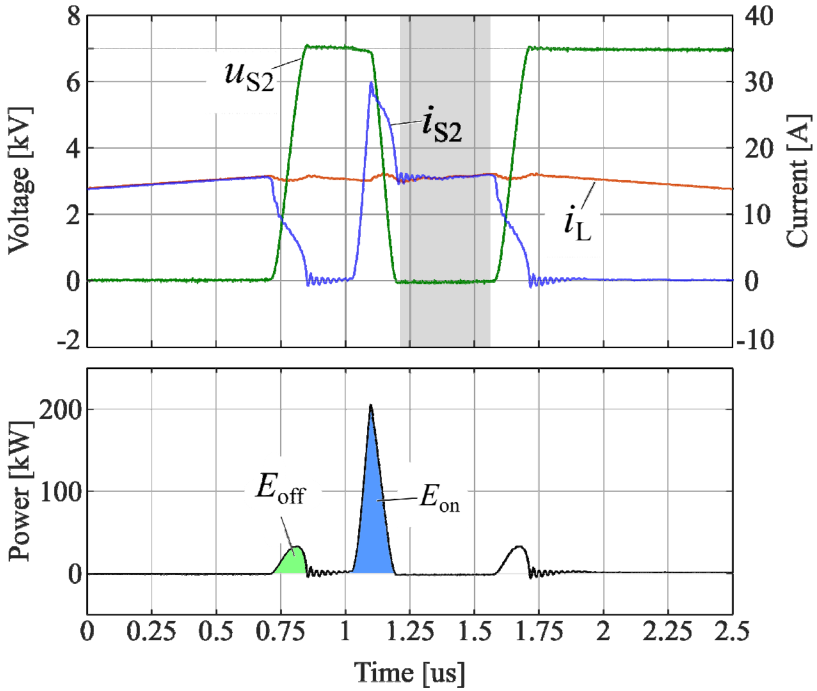
▶ Double Pulse Test (DPT)

Bridge Leg with Inductive Load



Hard Turn-On Transition ✓

▶ Hard-Switching



Switched Voltage
Inductor Current
Switched Current

Electric Measurement

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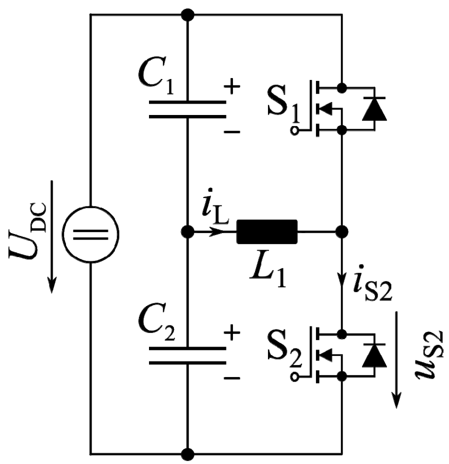

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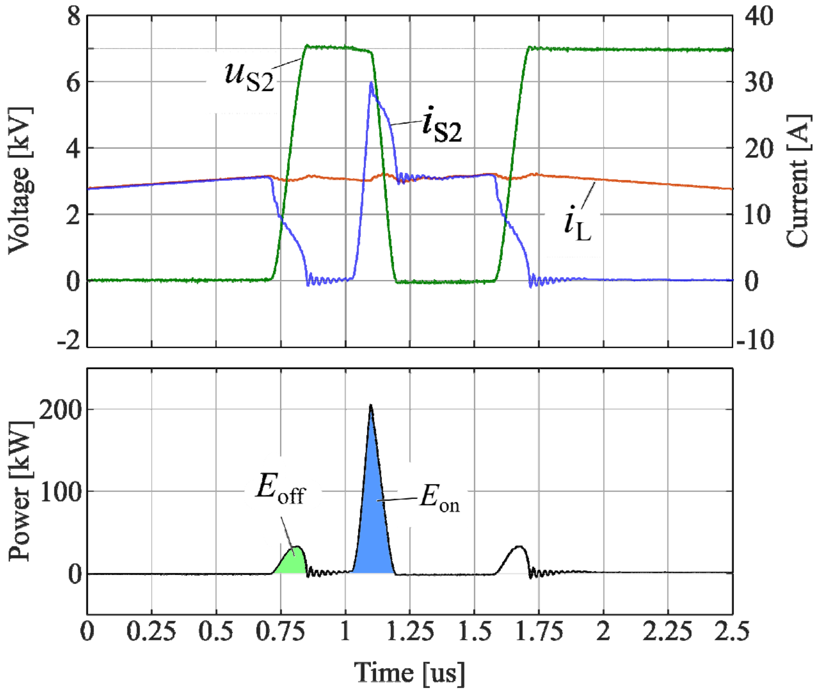


Switched Voltage
Inductor Current
Switched Current

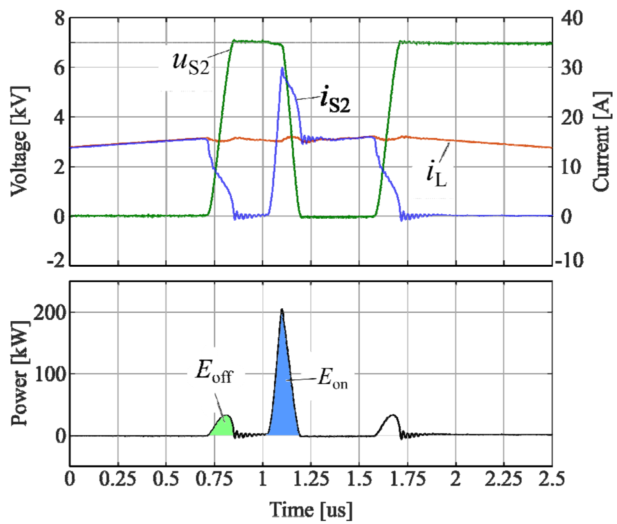
▶ Energy Losses

$E_{tot} = E_{on} + E_{off}$ where $E_{on} >> E_{off}$

Electric Measurement - Overview

▶ Double Pulse Test (DPT)

Bridge Leg with Inductive Load

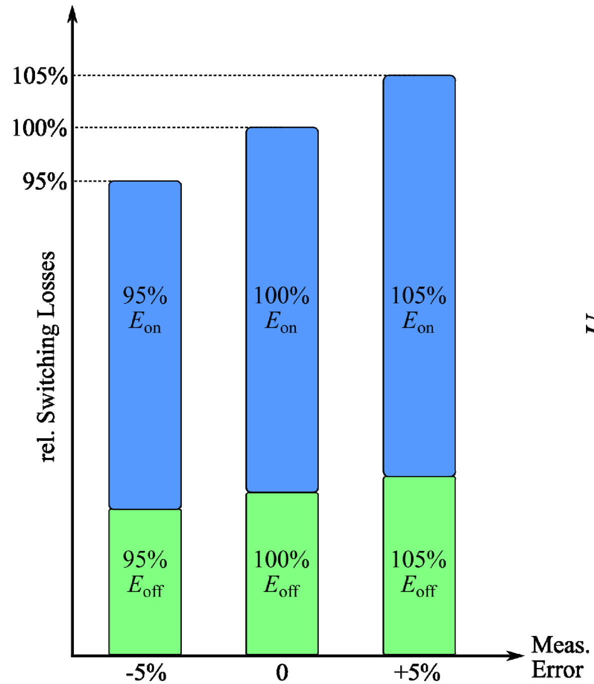


▶ Energy Losses

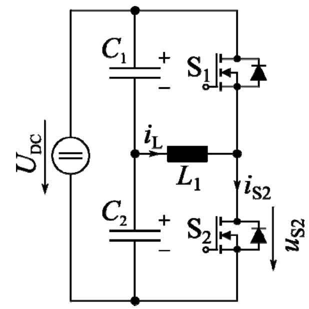
E_{on}, E_{off} > 0

$E_{tot} = E_{on} + E_{off}$

▶ Hard-Switching - Accuracy



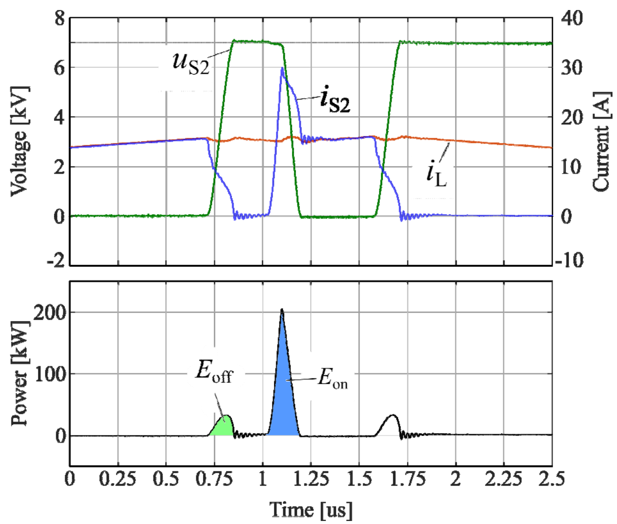
▶ DPT



Electric Measurement - Overview

▶ Double Pulse Test (DPT)

Bridge Leg with Inductive Load



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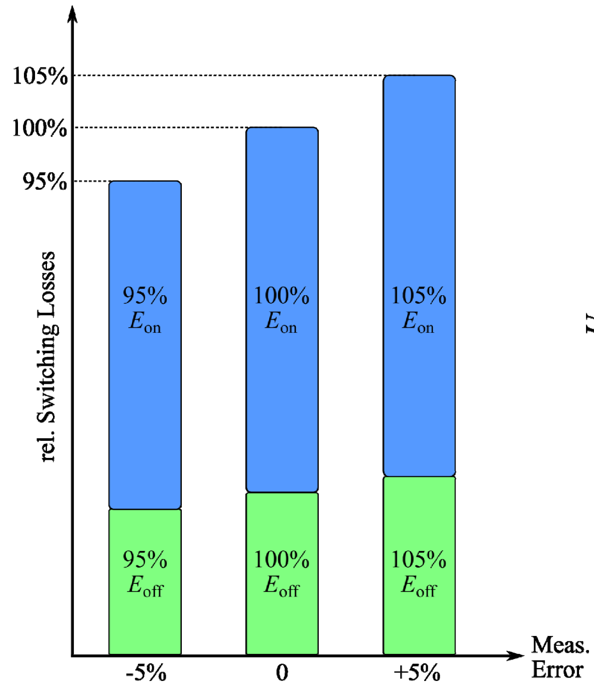

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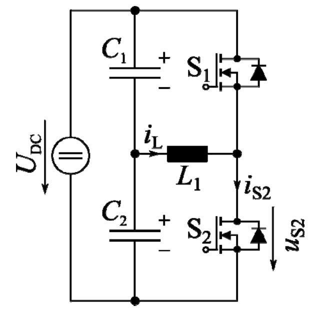


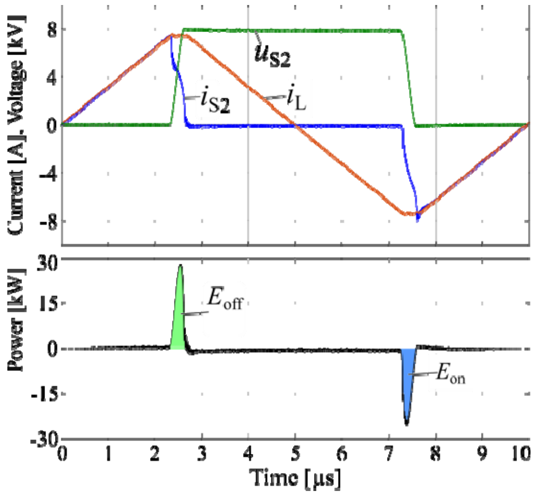
Worst Case ±5% and ±5%

→ ±5% of E_{tot} ✓

Electric Measurement - Overview

▶ Double Pulse Test (DPT)

Bridge Leg with Inductive Load



▶ Energy Losses

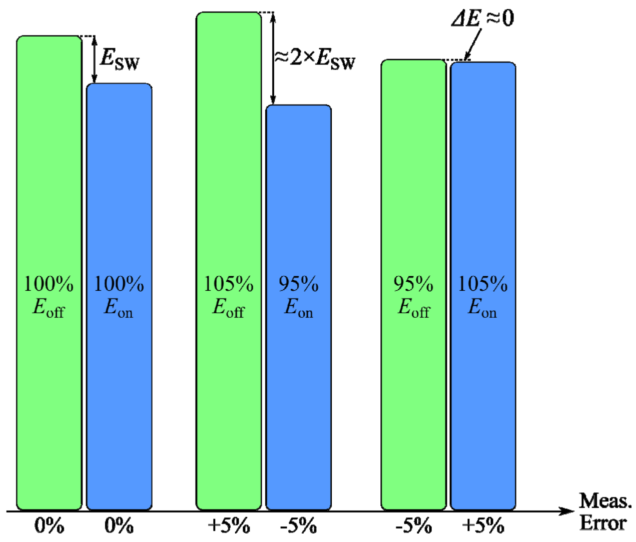
$E_{on} < 0$

$E_{off} > 0$

$E_{tot} = -|E_{on}| + E_{off}$

$|E_{on}| = 90\%\ E_{off}$

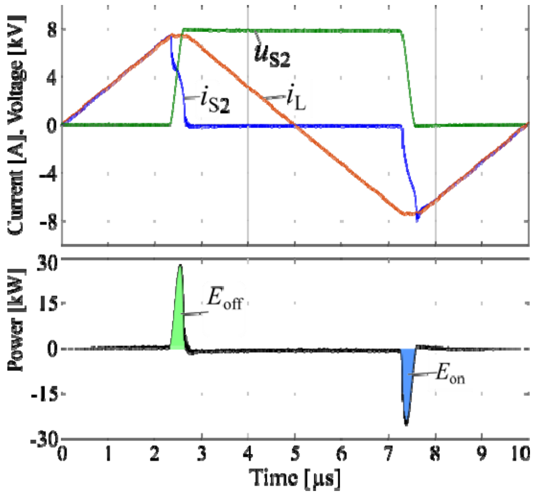
▶ Soft-Switching - Accuracy



Electric Measurement - Overview

▶ Double Pulse Test (DPT)

Bridge Leg with Inductive Load



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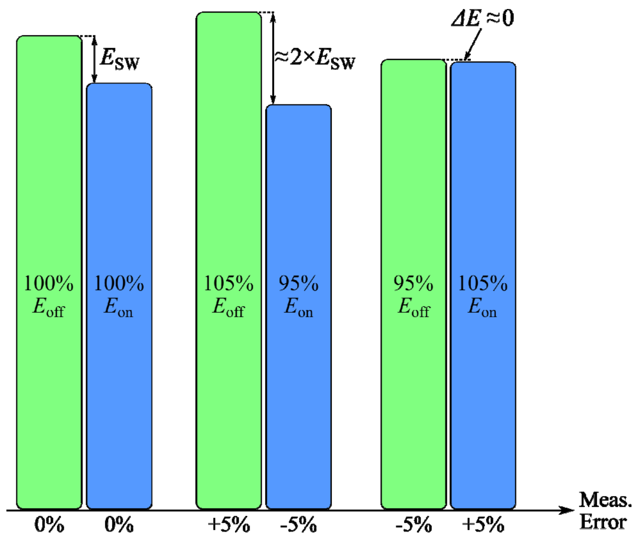


Worst Case 1: -5% and +5%

→ +100% of E_{tot} ✖ 2x Losses

Worst Case 2: +5% and -5%

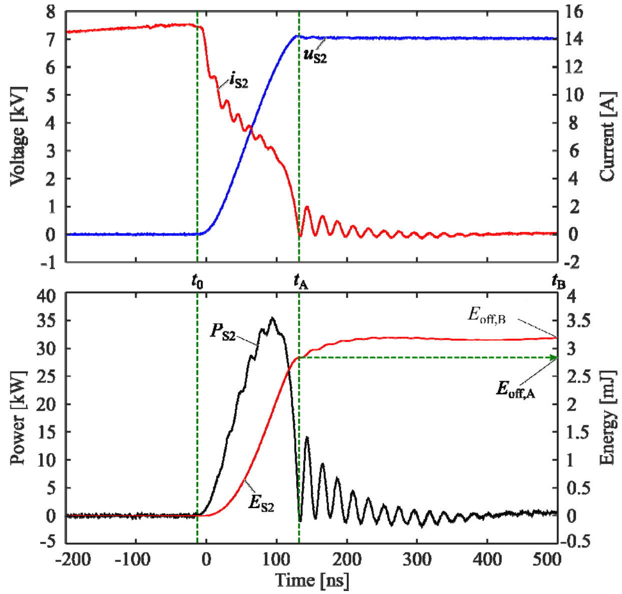
→ -100% of E_{tot} ✖ No Losses

Electric Measurement - Error

▶ Oscillation

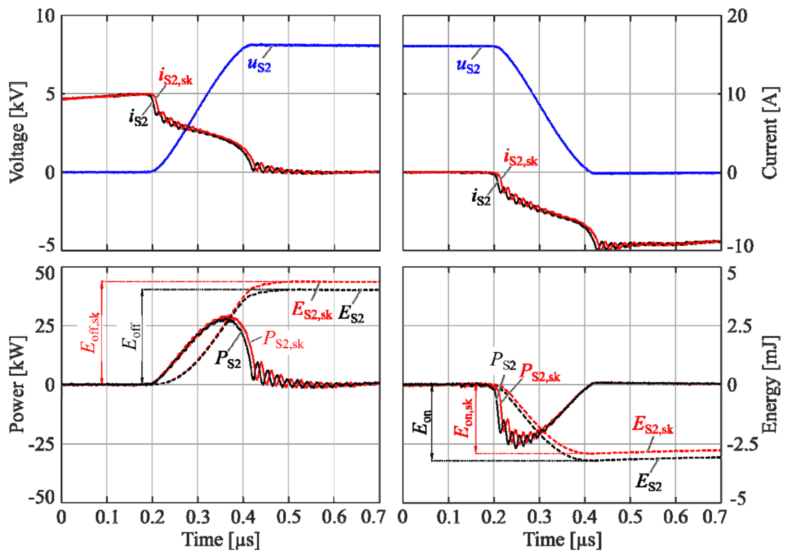
Boundaries of Power Integration

E_{tot} ±94.7% - E_{off} ±12.7%



▶ Voltage – Current Probes Skew

E_{tot} ±40% - 2ns Skew



▶ Others

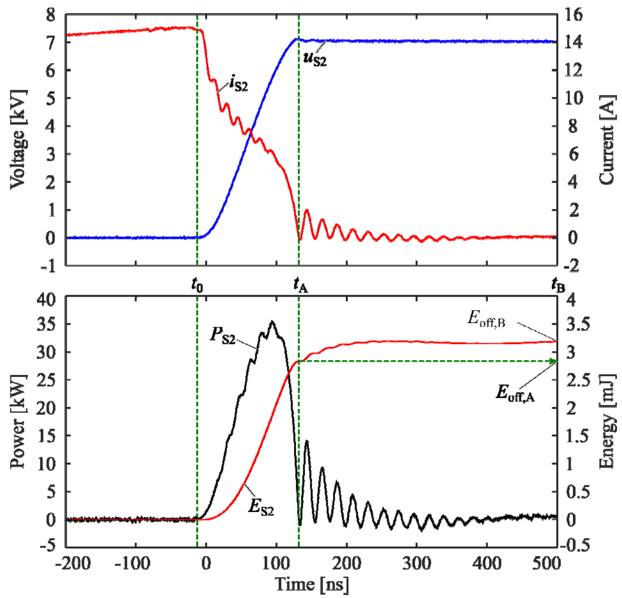
- Current and Voltage Offset
- Current and Voltage Amplitude
- Limited Bandwidth
- Ultra-Fast Switching (SiC, GaN)

Electric Measurement - Error

▶ Oscillation

Boundaries of Power Integration

E_{tot} ±94.7% - E_{off} ±12.7%



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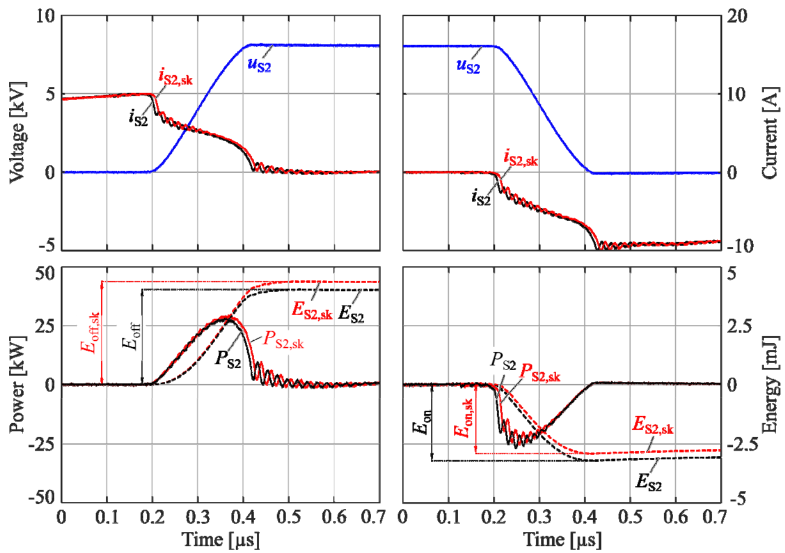


▶ Others

- Current and Voltage Offset
- Current and Voltage Amplitude
- Limited Bandwidth
- Ultra-Fast Switching (SiC, GaN)

▶ Accurate Calorimetric Method for Ultra-Fast Semiconductors

Accurate Calorimetric Method

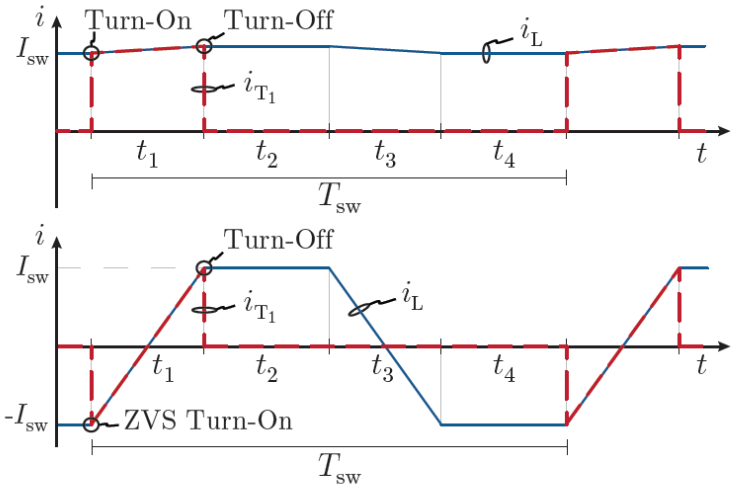
Air Flow Temperature Drop
Inductor in the Box
Bridge Leg in the Box
Precise Conduction Loss Estimation

Accurate Calorimetric Method

Air Flow Temperature Drop
Inductor in the Box
Bridge Leg in the Box
Precise Conduction Loss Estimation

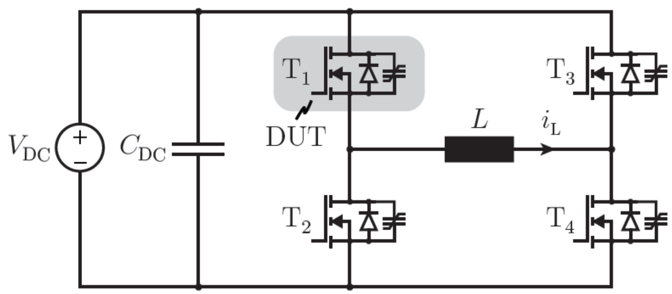
Air Flow Temperature Drop

▶ Improved DPT Method

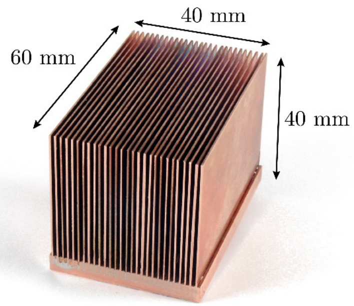


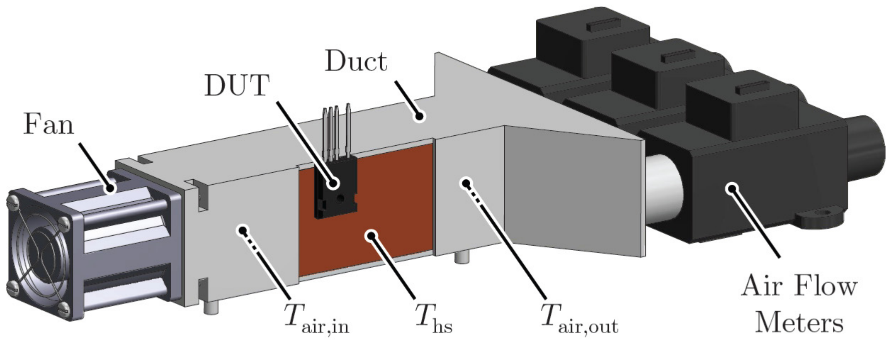
▶ Full-Bridge Configuration

Hard and Soft-Switching Operation



▶ Thermally Isolated DUT

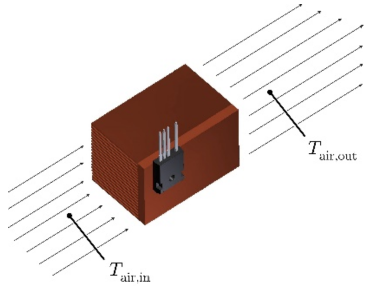




Air Flow Temperature Drop

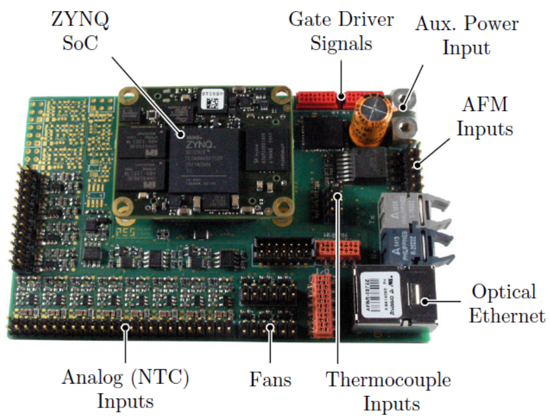
Loss Measurement

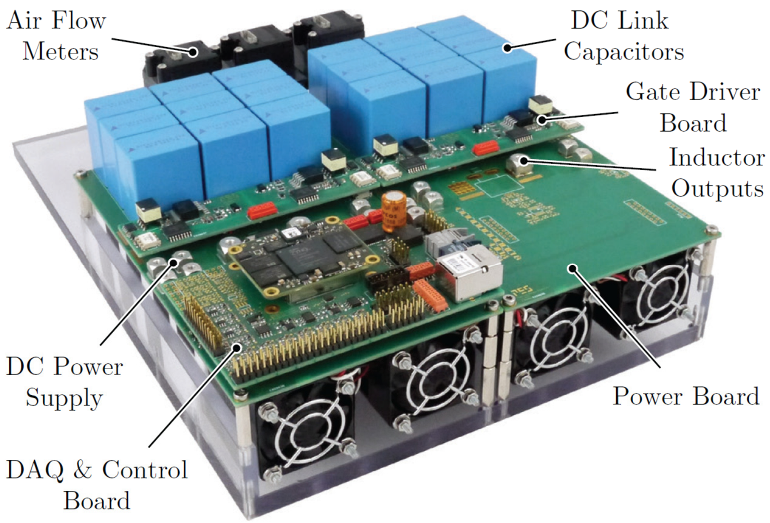
- $P_{loss} = k_1 (T_{hs} - T_{air,in})$ Thermal Resistance
- $P_{loss} = k_2 (T_{air,out} - T_{air,in})$ **Temperature Drop**
- $P_{loss} = k_3 (T_{air,out} - T_{air,in}) V$ Air Enthalpy Increase



$P_{loss} = P_{semi,th} = P_{cond} + P_{sw}$

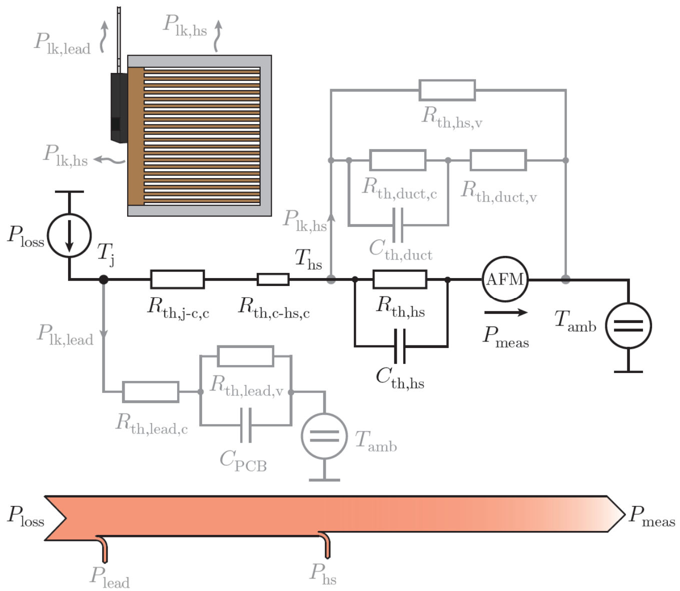
Measurement Setup

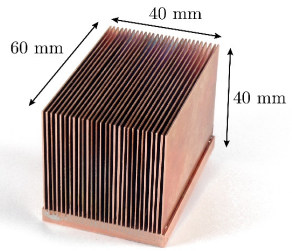




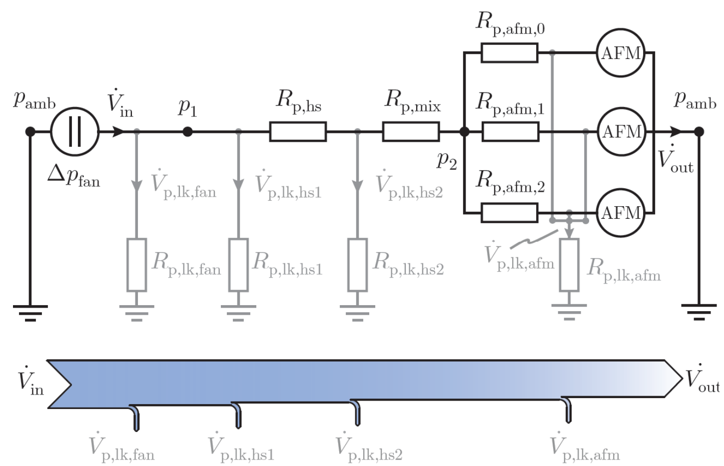
Air Flow Temperature Drop

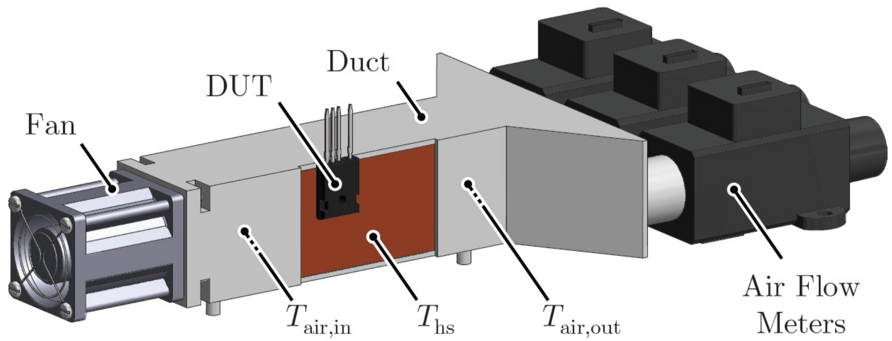
▶ Thermal Model





▶ Air Flow Model





Accurate Calorimetric Method

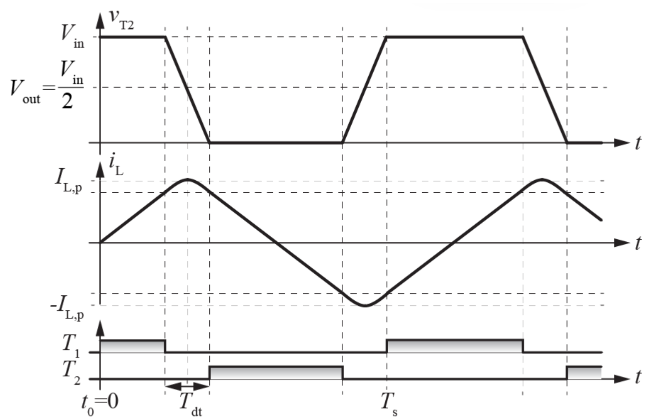
Air Flow Temperature Drop
Inductor in the Box
Bridge Leg in the Box
Precise Conduction Loss Estimation

Inductor in the Box

► Continuous TCM Operation

Soft-Switching Bridge Leg	P_{semi}
Output Inductor	$P_{ind,th}$
DC-Source	P_{in}

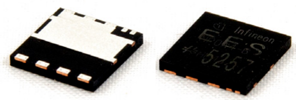
$$P_{in} - P_{ind,th} = P_{semi}$$

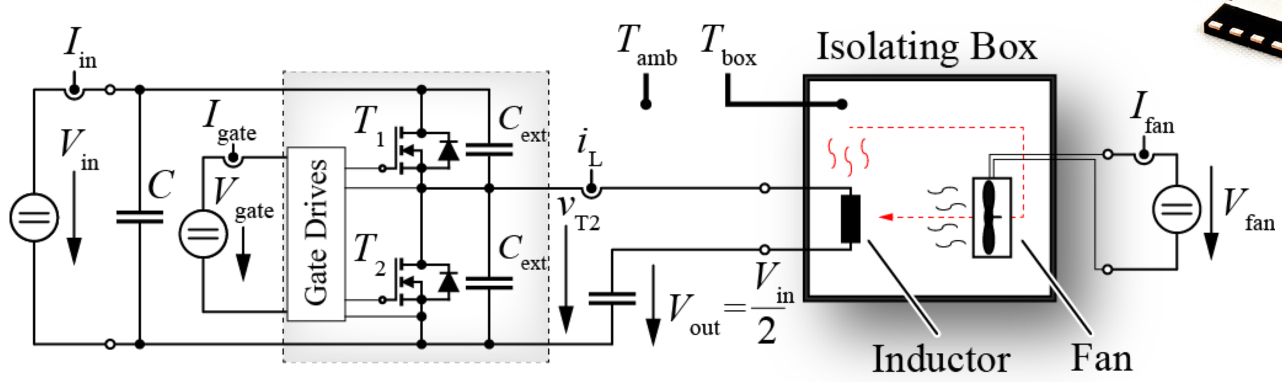


► Thermal Measurement

$$P_{ind,th} = R_{th,box}(T_{box} - T_{amb})$$

600V 65mΩ infineon GaN



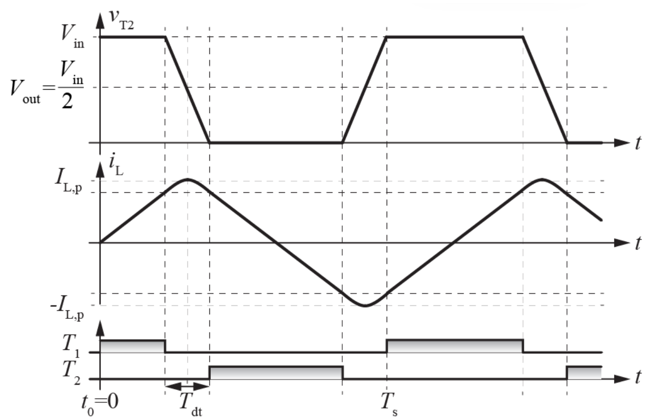


Inductor in the Box

► Continuous TCM Operation

Soft-Switching Bridge Leg	P_{semi}
Output Inductor	$P_{ind,th}$
DC-Source	P_{in}

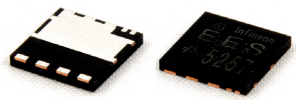
$P_{in} - P_{ind,th} = P_{semi} + P_{ext}$

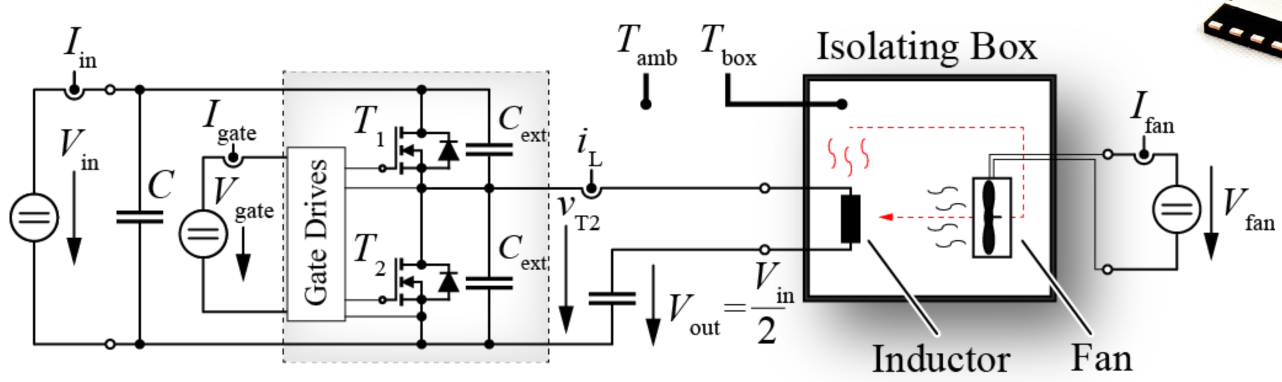


► Thermal Measurement

$P_{ind,th} = R_{th,box}(T_{box} - T_{amb})$ @ Steady-State

600V 65mΩ Infineon GaN





Accurate Calorimetric Method

Air Flow Temperature Drop
Inductor in the Box
Bridge Leg in the Box
Precise Conduction Loss Estimation

Bridge Leg in the Box

▶ Continuous TCM Operation

Soft-Switching Bridge Leg	$P_{semi,th}$
~~Output Inductor~~	P_{ind}
~~DC-Source~~	P_{in}

$$P_{semi,th} = P_{sw} + P_{cond}$$

▶ Thermal Measurement

$$P_{semi,th} = R_{th,box}(T_{box} - T_{amb})$$

Bridge Leg in the Box

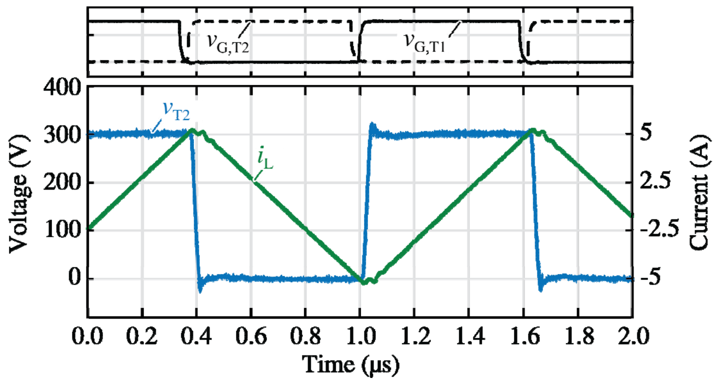
[3]

▶ Continuous TCM Operation

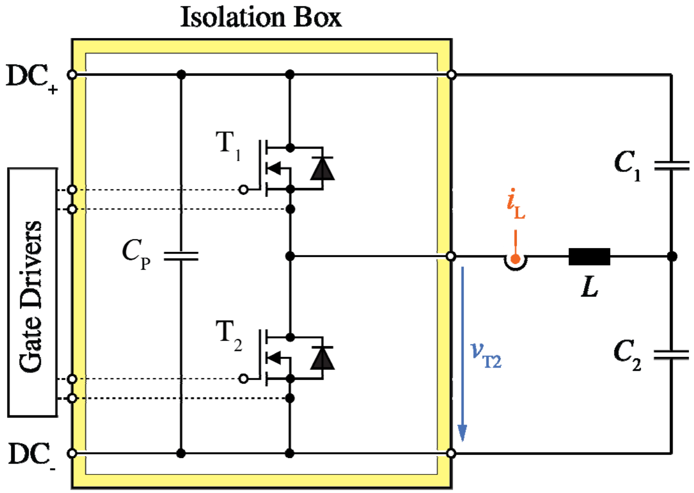
Soft-Switching Bridge Leg	$P_{semi,th}$
~~Output Inductor~~	P_{ind}
~~DC-Source~~	P_{in}

$$P_{semi,th} = P_{sw} + P_{cond}$$

▶ Measured Waveform



▶ Low-Voltage Setup



▶ **IMS**
Insulated
Metal
Substrate

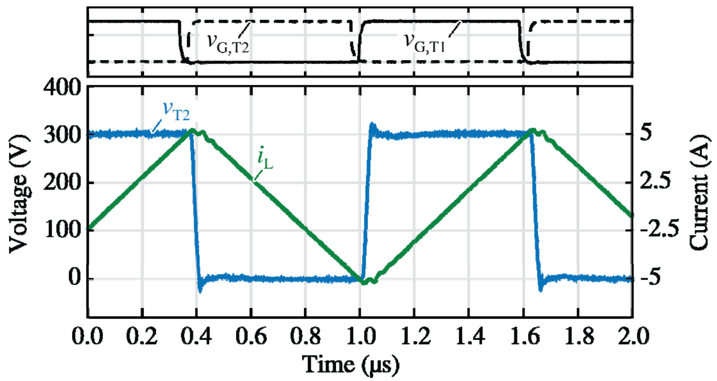
Bridge Leg in the Box

▶ Continuous TCM Operation

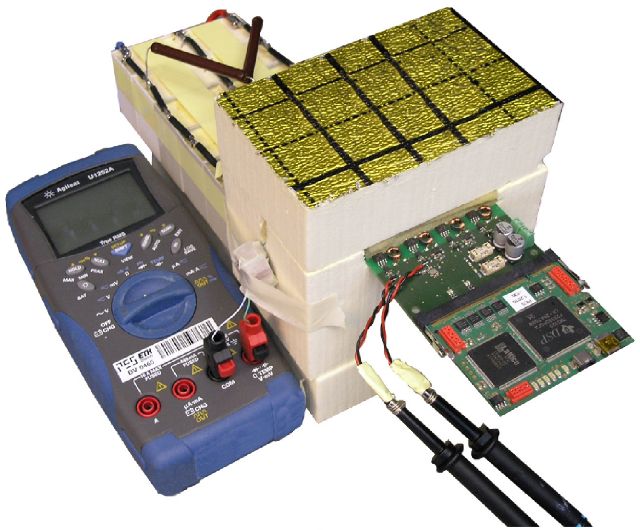
Soft-Switching Bridge Leg	$P_{semi,th}$
~~Output Inductor~~	P_{ind}
~~DC-Source~~	P_{in}

$P_{semi,th} = P_{sw} + P_{cond}$

▶ Measured Waveform



▶ Low-Voltage Setup

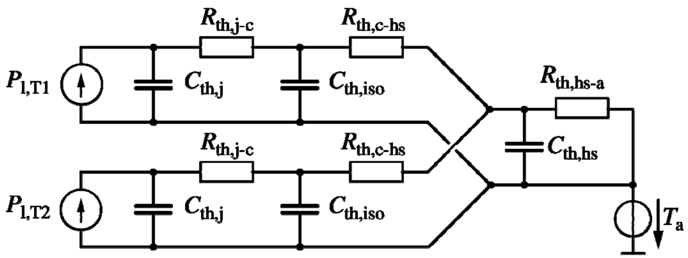


▶ IMS
Insulated
Metal
Substrate

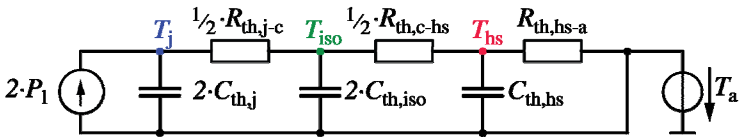
Bridge Leg in the Box

▶ Thermal System Analysis

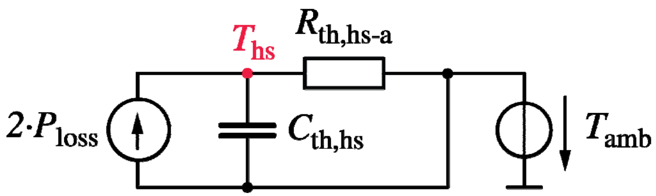
IMS Board + Heat-Sink + Box



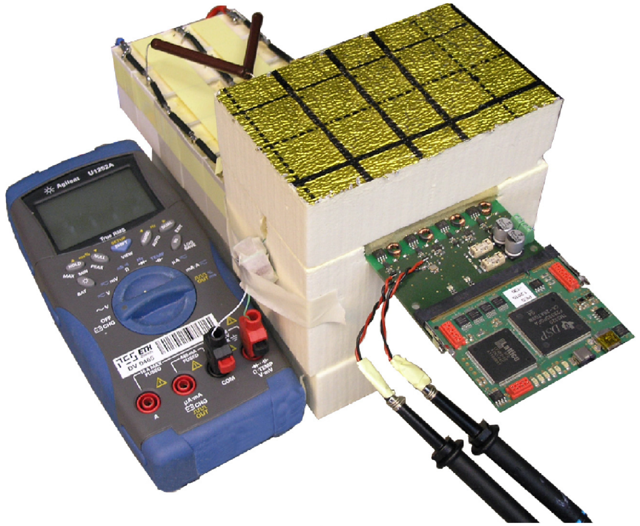
1st Hypothesis: Symmetry

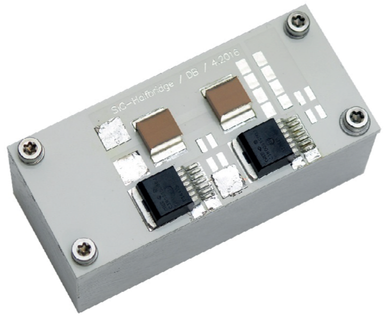


2nd Hypothesis: Slowest Time Constant



▶ Low-Voltage Setup



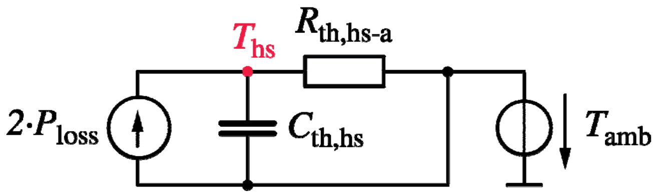


▶ IMS
Insulated
Metal
Substrate

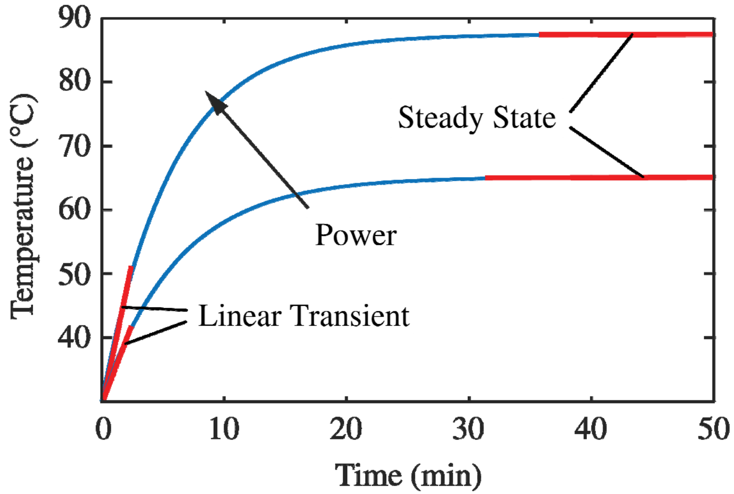
Bridge Leg in the Box

▶ Thermal System Calibration

Simplified: Slowest Time Constant



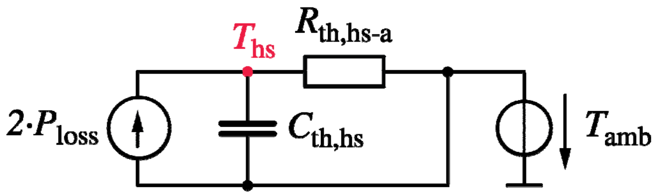
▶ Transient vs. Steady-State



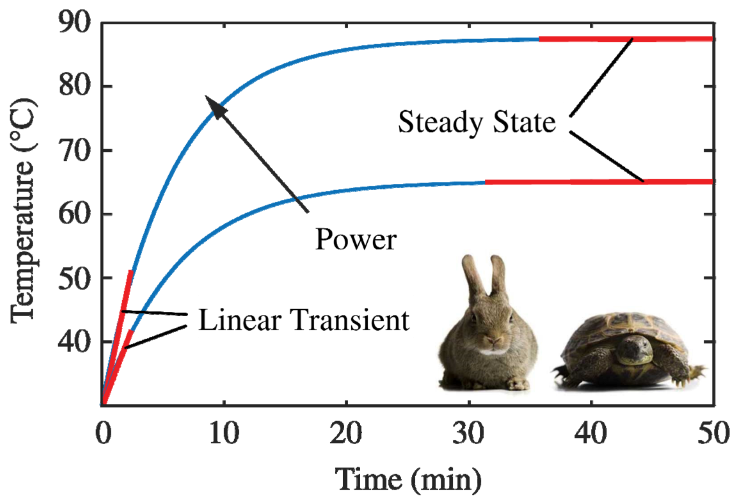
Bridge Leg in the Box

▶ Thermal System Calibration

Simplified: Slowest Time Constant



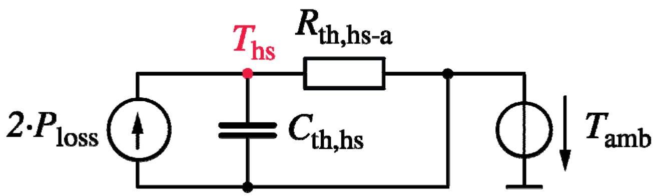
▶ Transient vs. Steady-State



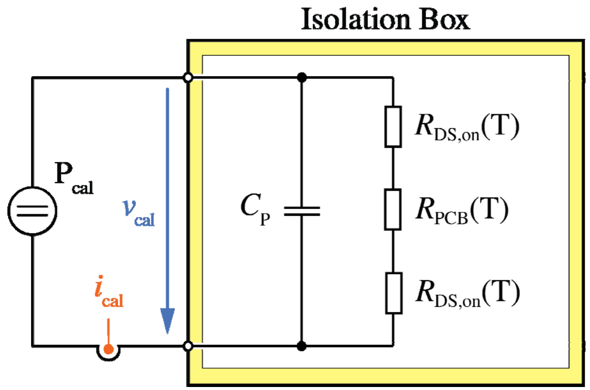
Bridge Leg in the Box

▶ Thermal System Calibration

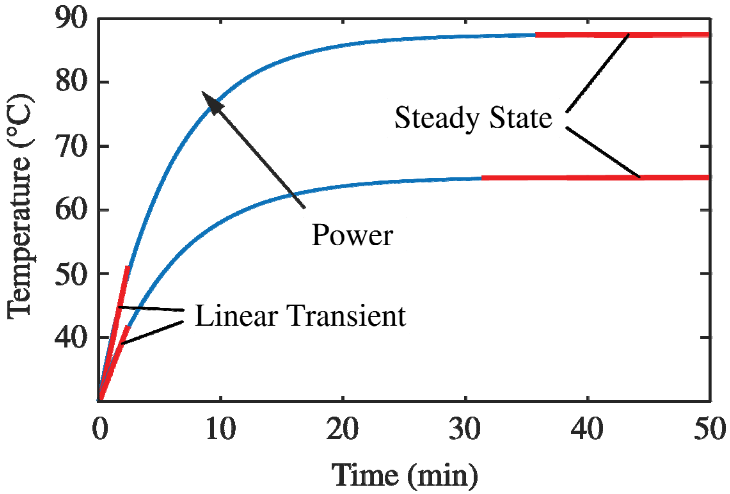
Simplified: Slowest Time Constant

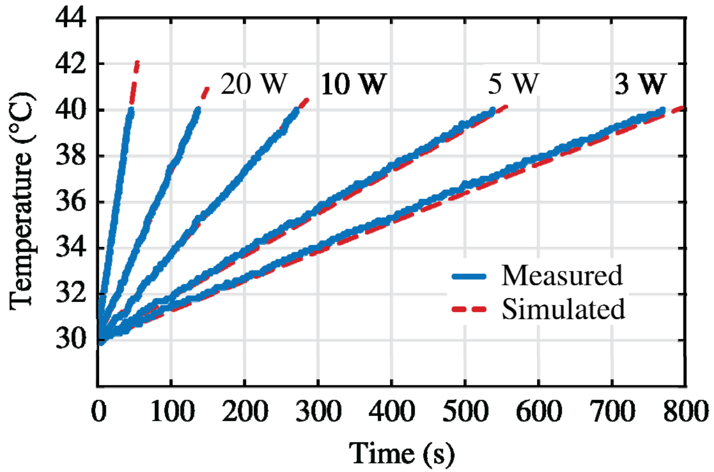


▶ DC-Calibration Setup



▶ Transient vs. Steady-State

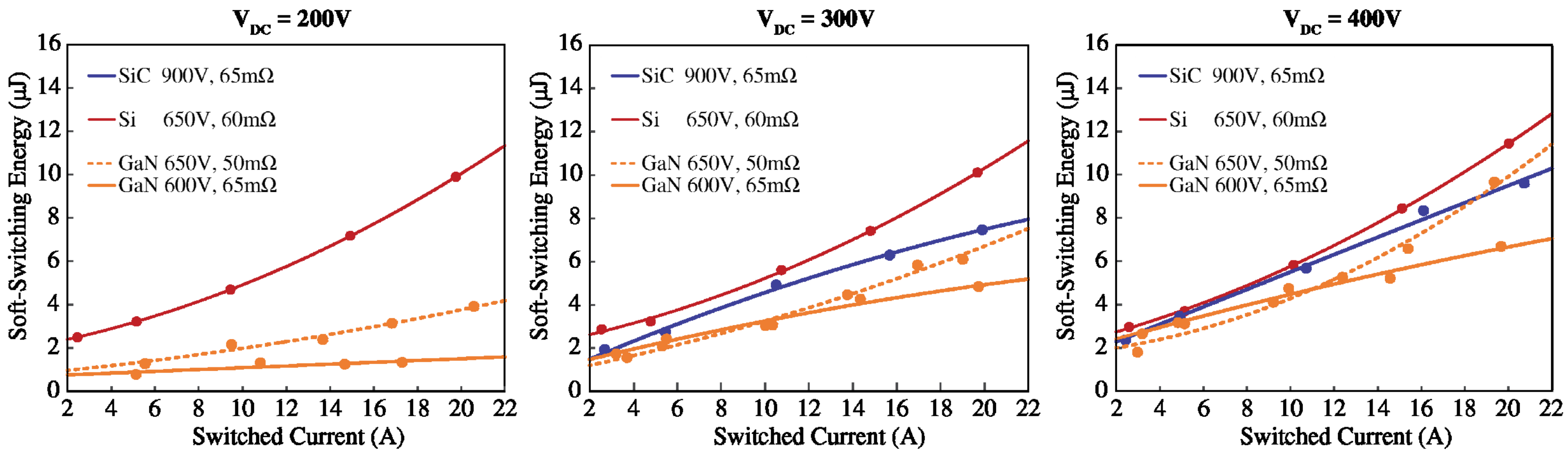




Bridge Leg in the Box

▶ Soft-Switching Loss Measurement

≈60mΩ 600V/650V/900V GaN, SiC and Si MOSFETs



E_{sw} per Switch and per Switching Period

▶ Si vs. SiC – GaN

- Gate-Driver and Resistance
- Parasitic Capacitance
- Power-Loop Inductance

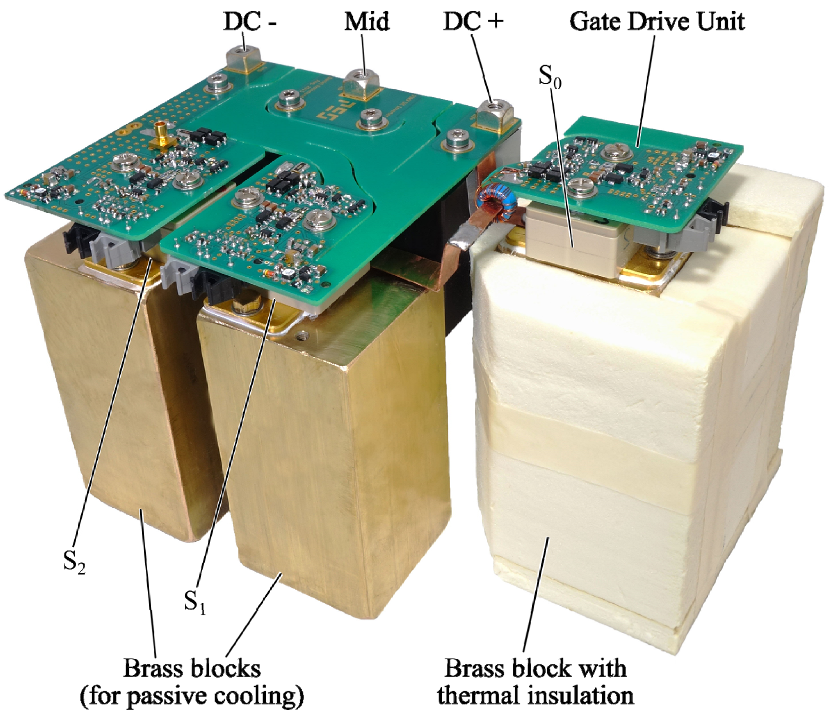
Type / Vendor	$V_{ds,max}$	$R_{ds,on}$	$Q_{g,tot}$	C_{oss}*	Package
GaN GIT	600 V	65 mΩ	-	100 pF	ThinPAK8x8
GaN E-HEMT	650 V	50 mΩ	5.8 nC	65 pF	GaNPX™
SiC MOSFET	900 V	65 mΩ	30.4 nC	80 pF	7LD2PAK
SiC MOSFET	650 V	60 mΩ	58.0 nC	50 pF	D2PAK
Si MOSFET	600 V	65 mΩ	68.0 nC	54 pF	ThinPAK8x8

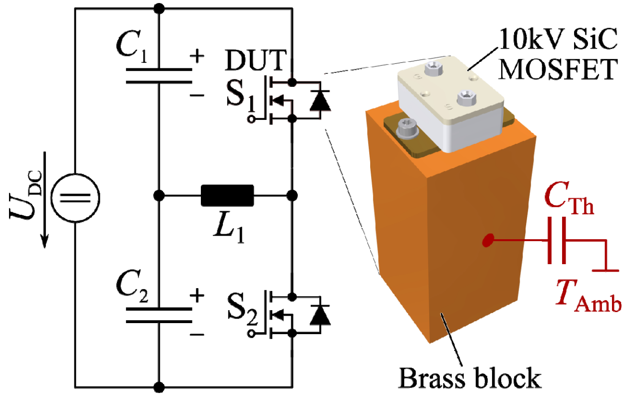
*400 V drain-source voltage

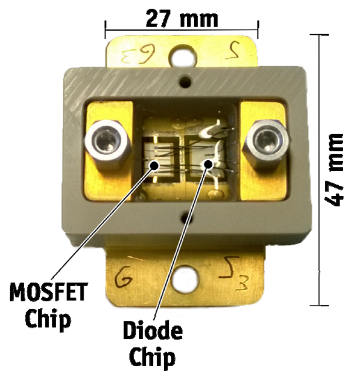
Bridge Leg in the Box

[2]

► Medium-Voltage Setup







30A 10kV SiC MOSFET

Accurate Calorimetric Method

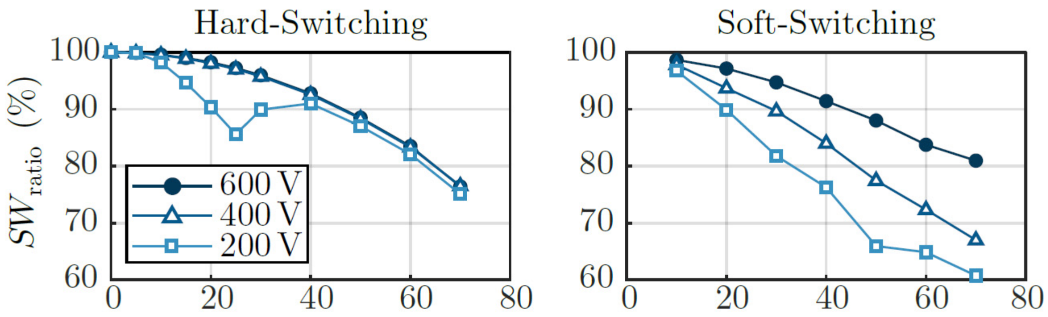
Air Flow Temperature Drop
Inductor in the Box
Bridge Leg in the Box
Precise Conduction Loss Subtraction

Conduction Loss - Accuracy

▶ Conduction Loss Subtraction

$P_{semi} - P_{cond} = P_{sw}$

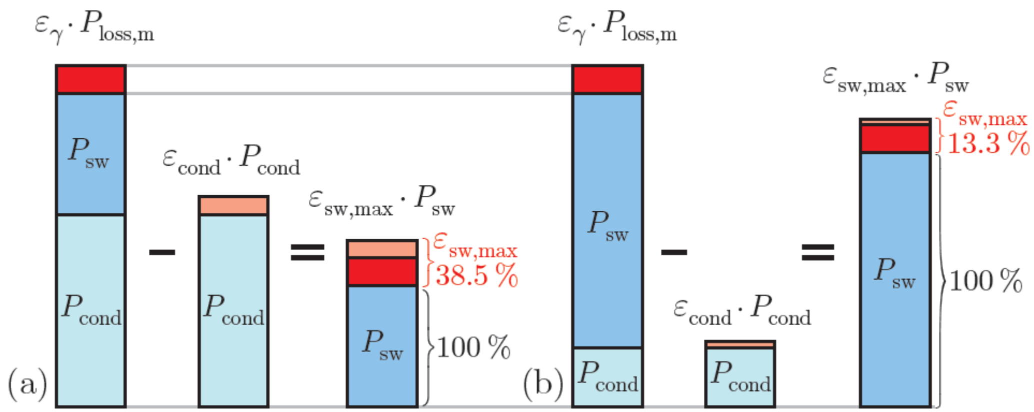
$S_{ratio} = P_{sw}/P_{loss}$



> 70% **> 60%**

e.g. @ 70A 600V_{DC}

- S_{ratio} = 38.7% (a)
  P_{sw} **±38.5%**
- S_{ratio} = 81.0% (b)
  P_{sw} **±13.3%**



Maximize S_{ratio}
in each operating point

Conduction Loss - Estimation

▶ Accurate Calorimetric Method

- Air Flow Temperature Drop
- Inductor in the Box
- Bridge Leg in the Box

$P_{semi,th} - P_{cond} = P_{sw}$

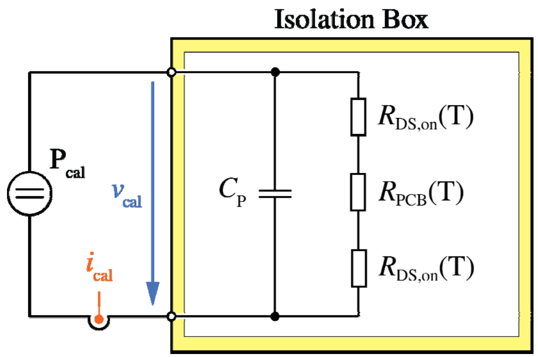
▶ $P_{cond} = R_{ds,on} I_{sw}^2$

$R_{ds,on} = r_{ds,on}(t, T, i_{sw}, f_{sw})$ $I_{sw} = i_{sw}(t)$

▶ $R_{ds,on}$ Evaluation

	Hardware	Accuracy
Datasheet Curve	++	--
DC-Calibration	+	+
3rd Switch Method	--	+
$V_{ds,on}$ Measurement	-	++

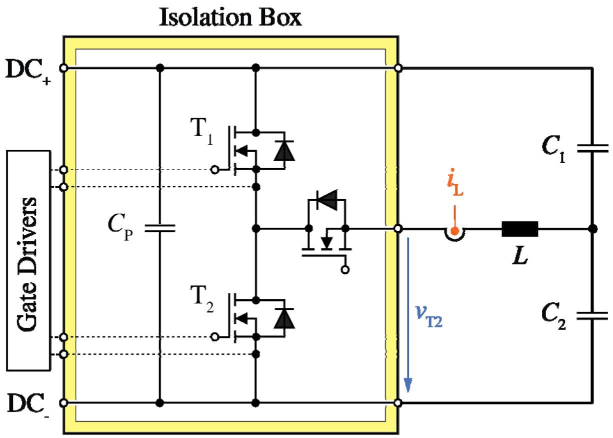
▶ DC-Calibration v_{cal}-i_{cal}



3rd Switch Method

▶ Low-Voltage Setup

2x Conduction Loss



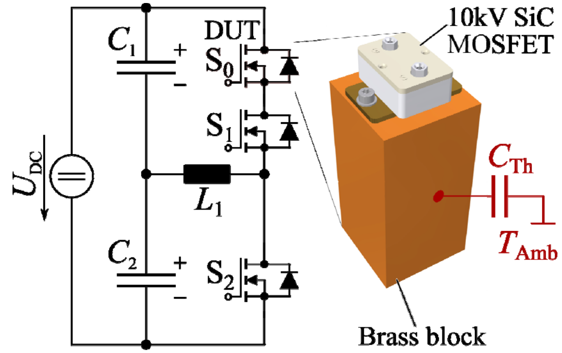
$P_{m2} = P_{sw} + 2\ P_{cond}$

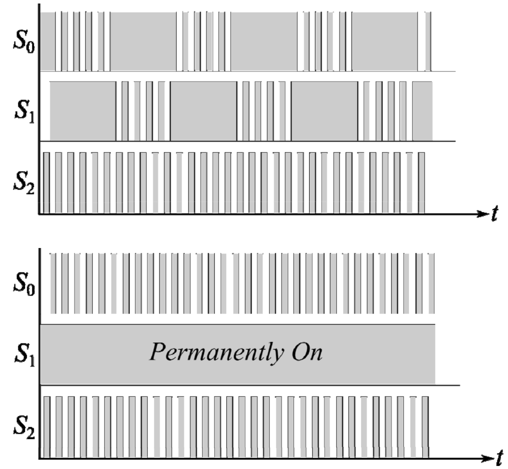
$P_{m2} - P_{m1} = P_{cond}$

$2\ P_{m1} - P_{m2} = P_{sw}$ ✔

▶ $P_{T3} \neq P_{T1}, P_{T2}$

▶ Medium-Voltage Setup





Improved Modulation Scheme

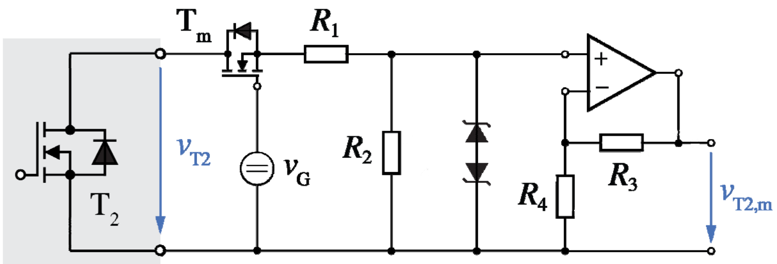
$V_{ds,on}$ Measurement

▶ Dynamic Range vs. Accuracy

Example: $60m\Omega$ - $20A_{FS}$

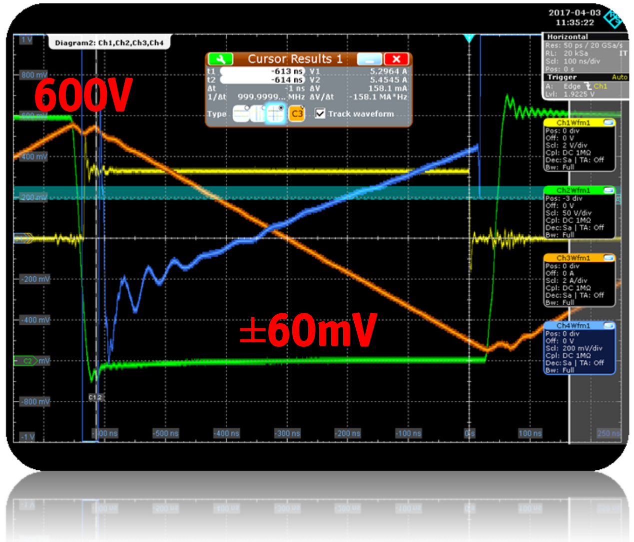
$V_{ds,on}$	$1.20V_{FS}$
Accuracy ±5%	±60mV
V_{DC}	600V

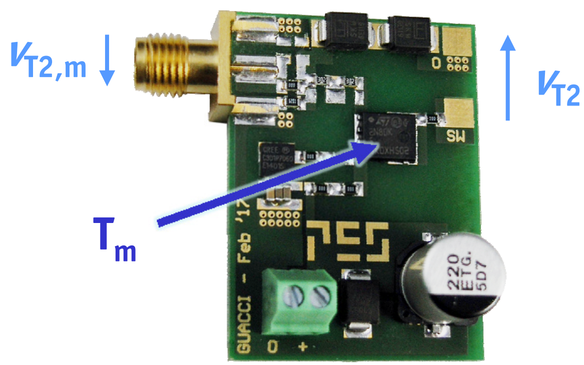
▶ De-Saturation Circuit



- Connected in Parallel to Low-Side MOSFET
- T_2 off: T_m Isolates the Measurement
- T_2 on: $v_{T2,m} = v_{T2}$ (≈5mV)

Response Time: 20ns





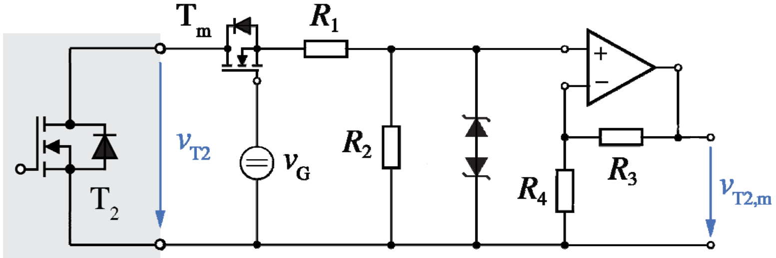
$V_{ds,on}$ Measurement

▶ Dynamic Range vs. Accuracy

Example: 60mΩ - $20A_{FS}$

$V_{ds,on}$	$1.20V_{FS}$
Accuracy ±5%	±60mV
V_{DC}	600V

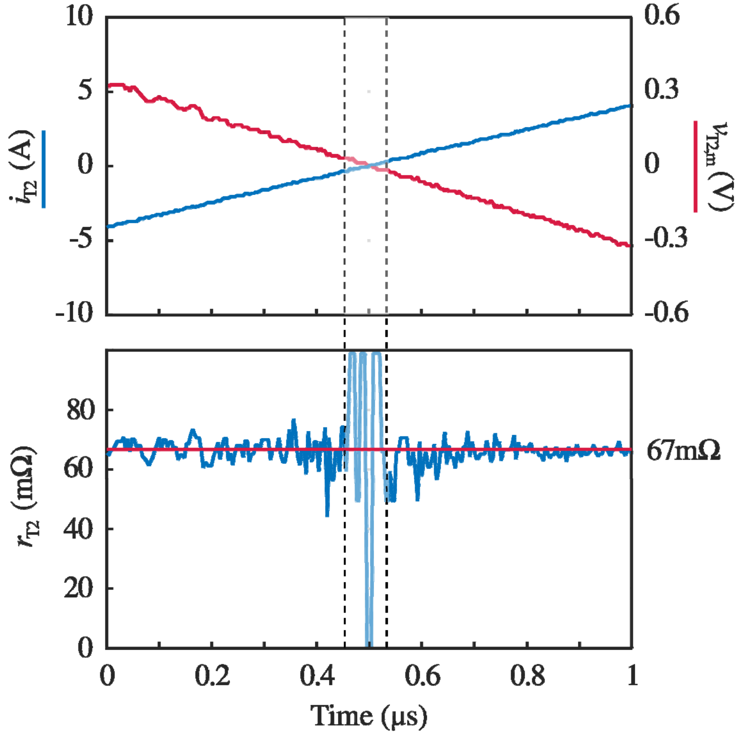
▶ De-Saturation Circuit



- Connected in Parallel to Low-Side MOSFET
- T_2 off: T_m Isolates the Measurement
- T_2 on: $v_{T2,m} = v_{T2}$ (≈5mV)

Response Time: 20ns

▶ Measurement Results



▶ Accurate $R_{ds,on}$ Measurement

Outline

- Impact of Switching Loss
- Conventional Measurement
- Accurate Calorimetric Measurement
- Conclusion - Outlook

Summary

► Conclusion

Conventional Electric Switching Loss Measurement are not enough for:

- Ultra-Fast Switching Semiconductors
- Soft-Switching Operation

Accurate Calorimetric Switching Loss Measurement Methods are proposed

High Accuracy Calorimetric Methods can be set up but:

- Good knowledge of the Thermal Setup must be acquired
- S_{ratio} must be kept as high as possible (e.g. f_{sw}, duty-cycle, ...)
- Conduction Losses must be accurately estimated

► Outlook

- Analyse the Soft-Switching Loss Mechanisms and Dependencies
- Validate Accuracy Estimation
- Extend the Measurements to Other Devices
- Validate Measurement Results in a Power-Converter Setup

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ETH Zurich
General

▶ Power Electronic System Laboratory – ETH Zurich

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[2] **D. Rothmund, D. Bortis, J. W. Kolar**, "Accurate Transient Calorimetric Measurement of Soft-Switching Losses of 10kV SiC MOSFETs," Proceedings of the 7th International Symposium on Power Electronics for Distributed Generation Systems (PEDG 2016), Vancouver, Canada, June 27-30, 2016.

[3] **D. Neumayr, M. Guacci, D. Bortis, J. W. Kolar**, "Novel Temperature-Gradient based Calorimetric Measurement Principle to Obtain Soft-Switching Benchmark of GaN and SiC Power Devices," Proceedings of the 29th IEEE International Symposium on Power Semiconductor Devices and ICs (ISPSD 2017), Sapporo, Japan, May 28 - June 1, 2017.

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Biographies of the Contributors

Mattia Guacci (SM'16) studied Electronic Engineering at the University of Udine, Italy. In July 2013 he received his B.Sc. summa cum laude and in October 2015 he received his M.Sc. summa cum laude and honorable mention presenting a thesis entitled "Bidirectional High-Efficiency Isolated DC-DC Multi-Resonant Power Converters for Active Suspension Systems". In 2014 he was with Metasystems SpA in Reggio nell'Emilia, Italy working on battery electric vehicle on-board battery chargers.
In November 2015 he joined the Power Electronic Systems Laboratory (PES) at ETH Zurich as a scientific assistant investigating innovative inverter topologies. In September 2016 he started his Ph.D. at PES focusing on integrated modular high-efficiency and weight optimized power electronic converters for aircraft application.

Dominik Neumayr (SM'10) started his academic education at the University of Applied Sciences (FH) for Automation Engineering in Wels and received the Dipl.-Ing. (FH) degree in 2008. He was with the Center for Advanced Power Systems (CAPS) in Tallahassee/Florida working on Power/Controller Hardware-in-the-Loop simulations and control systems design for AC/DC/AC PEBB based converter systems from ABB. He continued his academic education at the Swiss Federal Institute of Technology in Zurich (ETH Zurich) and received the M.Sc. degrees in electrical engineering and information technology in 2015. Since spring 2015 he is a PhD student at the Power Electronic Systems (PES) Laboratory, ETH Zurich. His current research focuses on ultra-high power density converter systems.

Daniel Rothmund (SM´14) Daniel Rothmund was born in Donaueschingen, Germany, in January 1989. He studied electrical engineering and information technology at ETH Zurich with the focus on power electronics, high voltage technology, electric power systems and acoustics, receiving his MSc degree in April 2013. During his master thesis he designed and constructed a 80kW medium voltage back-to-back series resonant converter system at the Power Electronic Systems Laboratory, ETH Zurich, where he started working as a PhD student in April 2013.

Jon Azurza Anderson (SM´16) Jon Azurza Anderson, born in 1992, is from Donostia - San Sebastián, Basque Country, Spain. He received his BSc degree in Industrial Technologies Engineering at TECNUN School of Engineering of the University of Navarra, in 2014, where he also spent a semester at the University of Hong Kong as an exchange student. During his studies, he did two industry internships at the Fraunhofer Insitute for Integrated Circuits, in Nuremberg, Germany. He continued his electrical engineering MSc studies at ETH Zürich, graduating in 2016, where he focused on power electronics, power systems and high voltage technology. For his master's thesis he developed a novel concept of switching loss measurements for power transistors. He joined the Power Electronic Systems Laboratory as a scientific assistant in October 2016, and began his PhD in February 2017, where he is focusing on ultra-efficient AC/DC/AC converters.

Dominik Bortis (M´08) received the M.Sc. degree in electrical engineering and the Ph.D. degree from the Swiss Federal Institute of Technology (ETH) Zurich, Switzerland, in 2005 and 2008, respectively. In May 2005, he joined the Power Electronic Systems Laboratory (PES), ETH Zurich, as a Ph.D. student. From 2008 to 2011, he has been a Postdoctoral Fellow and from 2011 to 2016 a Research Associate with PES, co-supervising Ph.D. students and leading industry research projects. Since January 2016 Dr. Bortis is heading the newly established research group Advanced Mechatronic Systems at PES.

Johann W. Kolar (F´10) received his Ph.D. degree (summa cum laude) from the Vienna University of Technology, Austria. He is currently a Full Professor and the Head of the Power Electronic Systems Laboratory at the Swiss Federal Institute of Technology (ETH) Zurich. He has proposed numerous novel PWM converter topologies, and modulation and control concepts and has supervised over 60 Ph.D. students. He has published over 750 scientific papers in international journals and conference proceedings, 3 book chapters, and has filed more than 140 patents. He has received 25 IEEE Transactions and Conference Prize Paper Awards, the 2014 IEEE Power Electronics Society R. David Middlebrook Achievement Award, the 2016 IEEE William E. Newell Power Electronics Award, and the 2016 IEEE PEMC Council Award. He has initiated and/or is the founder of 4 ETH Spin-off companies.

Thank You !