ETH zürich

Advanced Measurement Technology for Power Electronics Systems

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ETH Zurich, Switzerland

PCIM SOUTH AMERICA

Keynote

Agenda

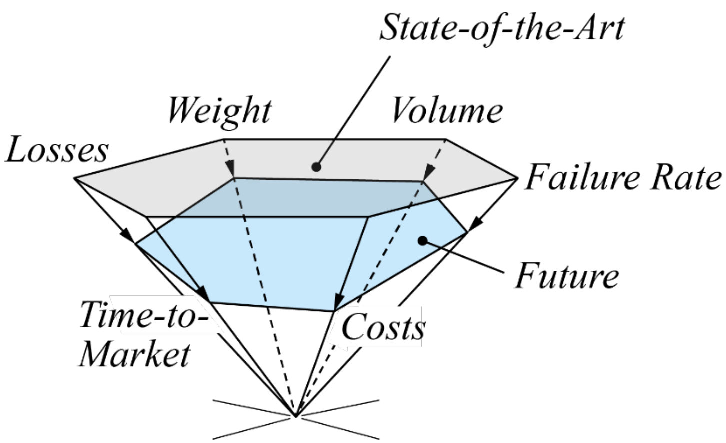
Introduction	Measuring Today: Componets	Measuring Today: System	Measuring in the Future	Summary Outlook
13 slides	27 slides	9 slides	13 slides	1

Introduction

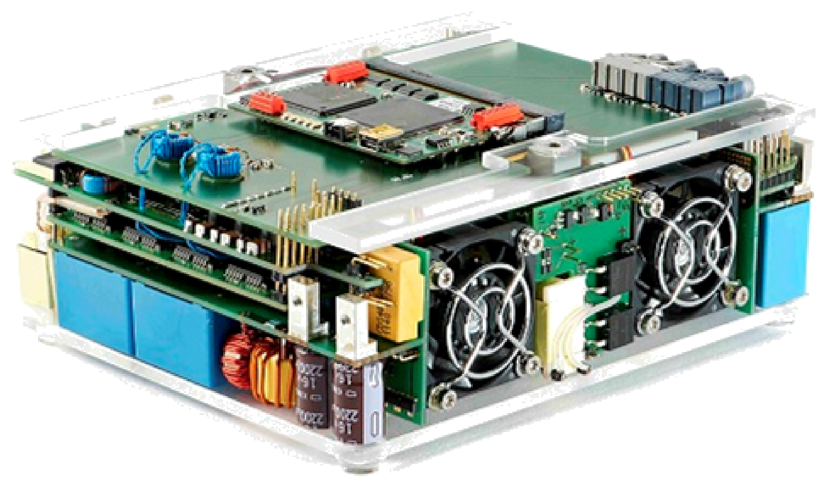
Power electronics' designer goal
Typical and future power electronics measurement situations

▶ Power Electronics Engineer Goal

- Design a power electronic system which complies with a certain set performance indices



Source: Ch. Gammeter
Converter for airborn wind turbine

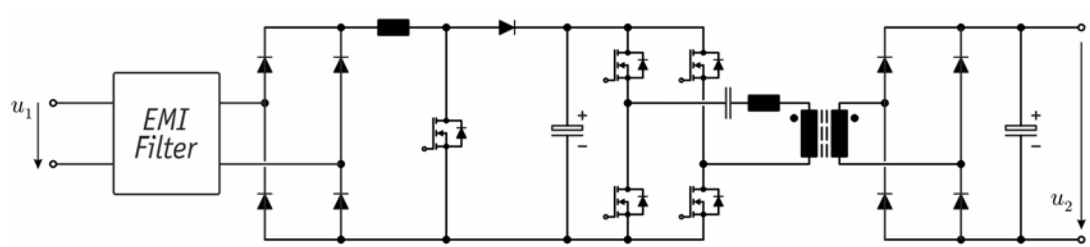


- **Performance Indices**

• Power density	[kW/dm^3]
• Power per unit weight	[kW/kg]
• Relative costs	[kW/$]
• Relative losses	[%]
• Failure rate	[h^{-1}]

► Assessing System's Performance

- Translation of system requirements into components' requirements
- Example: boost-type PFC rectifier with resonant-type isolation DC-DC converter stage



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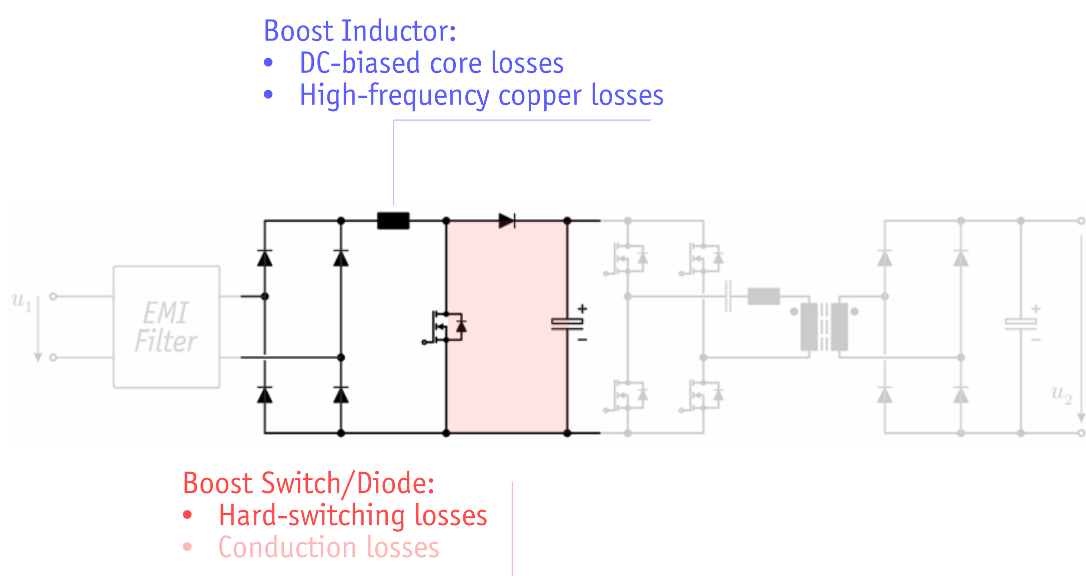
- Boost-type rectifier



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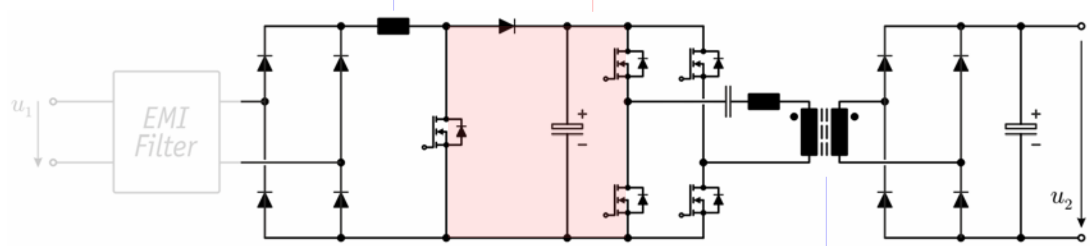
- Boost-type rectifier
- Isolated DC-DC converter



► Assessing System's Performance

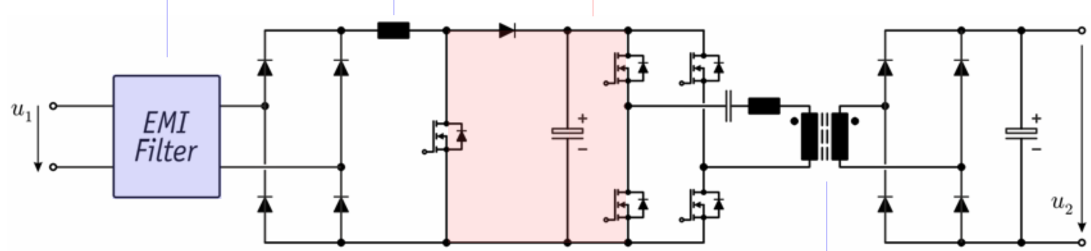
- Translation of system requirements into components' requirements
- Example: boost-type PFC rectifier with resonant-type isolation DC-DC converter stage

- Boost-type rectifier
- Isolated DC-DC converter
- EMI Filter

EMI Filter:
- Common-mode
- Differential-mode

Boost Inductor:
- DC-biased core losses
- High-frequency copper losses

DC-DC converter switches:
- Soft-switching losses (ZVS/ZCS)
- Conduction losses



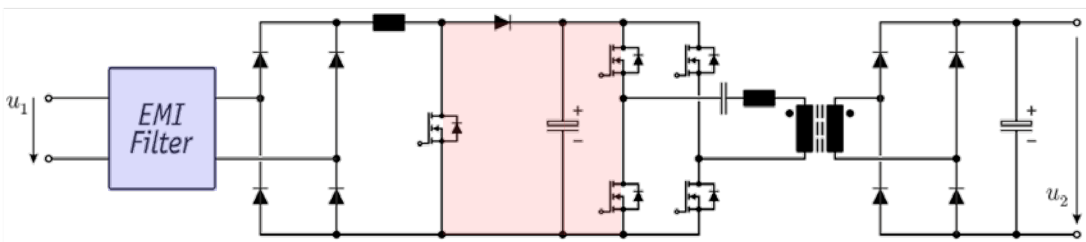
Boost Switch/Diode:
- Hard-switching losses
- Conduction losses

Isolation Transformer:
- Non-sinusoidal core excitation
- Litz wire high-frequency losses

► Assessing System's Performance

- Translation of system requirements into components' requirements
- Example: boost-type PFC rectifier with resonant-type isolation DC-DC converter stage

- Boost-type rectifier
- Isolated DC-DC converter
- EMI Filter
- **Efficiency**



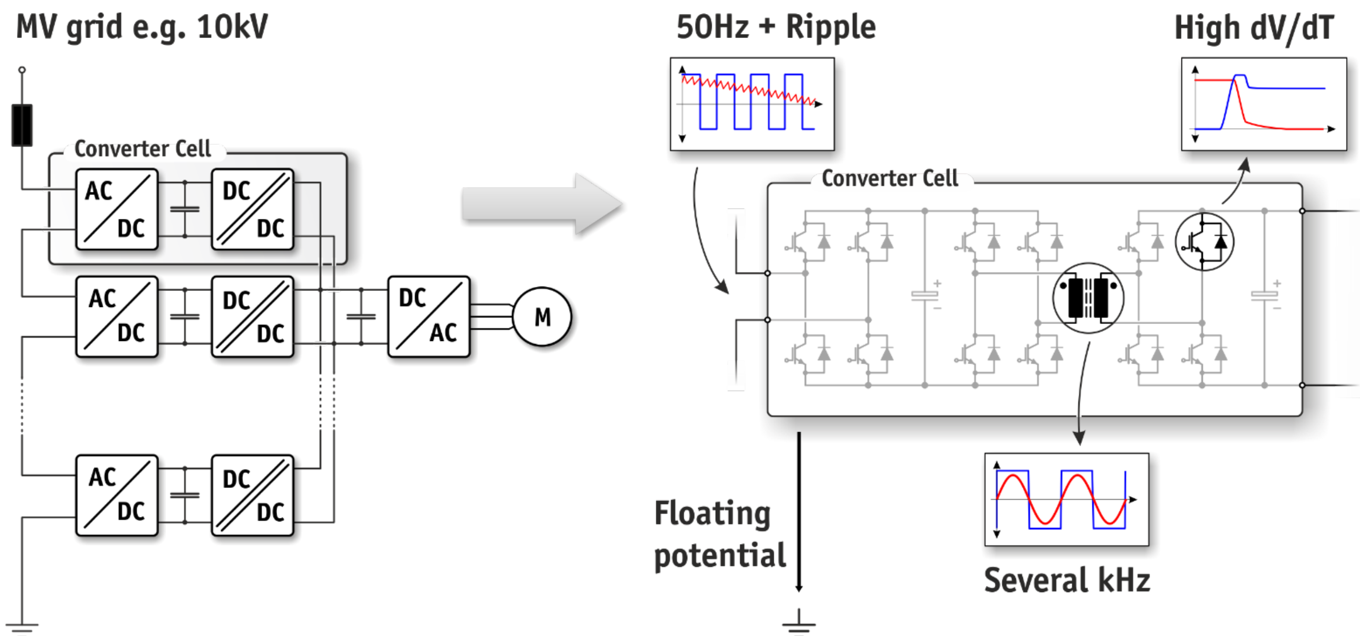
- **The performance of the complete system is defined by the performance of its individual components**

Introduction

Power electronics' designer goal
Typical and future power electronics measurement situations

► Future Traction Vehicles Based on SST Technology

- Typical measurements performed during testing and commissioning of power electronic converters



- **Floating potentials:** **Up to tens of kilovolts and tens of kilovolts/microsecond**
- Voltages / currents: From millivolts to kilovolts, from amps to kiloamps, **DC to tens of MHz**

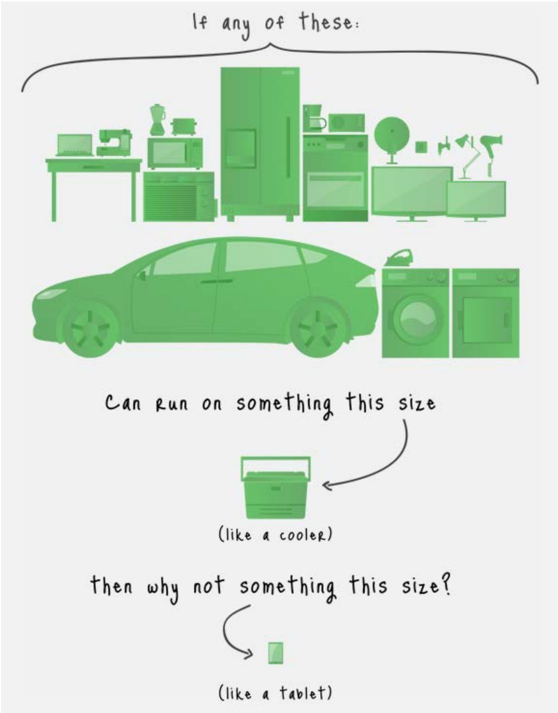
▶ Future Micro Power Electronic Solutions

- Vicor highly integrated power supplies
- The little box challenge

Up to 1750W (!)
Isolated DC-DC converter

www.vicorpower.com

www.littleboxchallenge.com

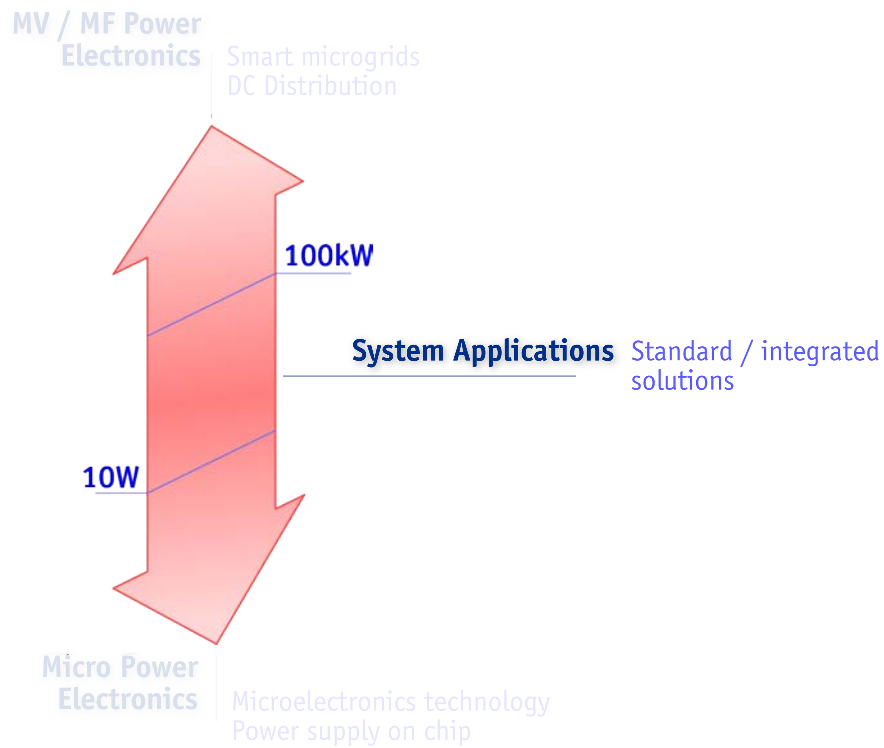


INTRODUCING THE LITTLE BOX CHALLENGE

- **Big challenges during testing and debugging of the converter system!**

► Today, Soon, and Future of Power Electronics…

- **Today:** **System Applications** Standard / integrated solutions



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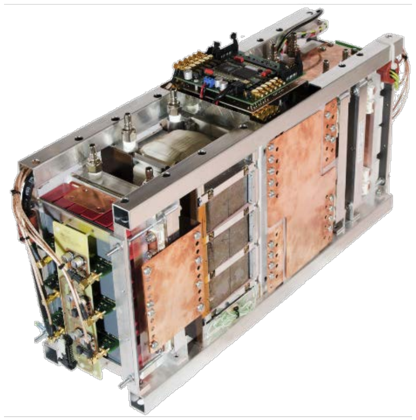

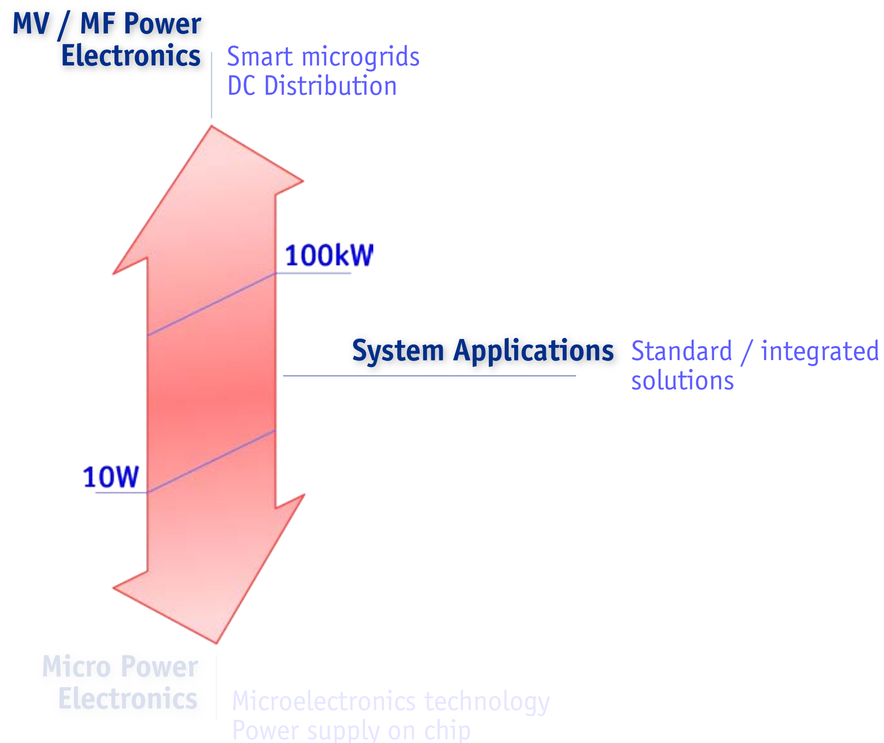

- **Future (Soon):** **Medium Freq. Medium Volt.** Smart microgrids, DC distribution

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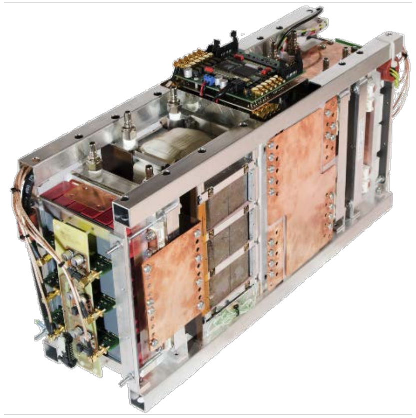
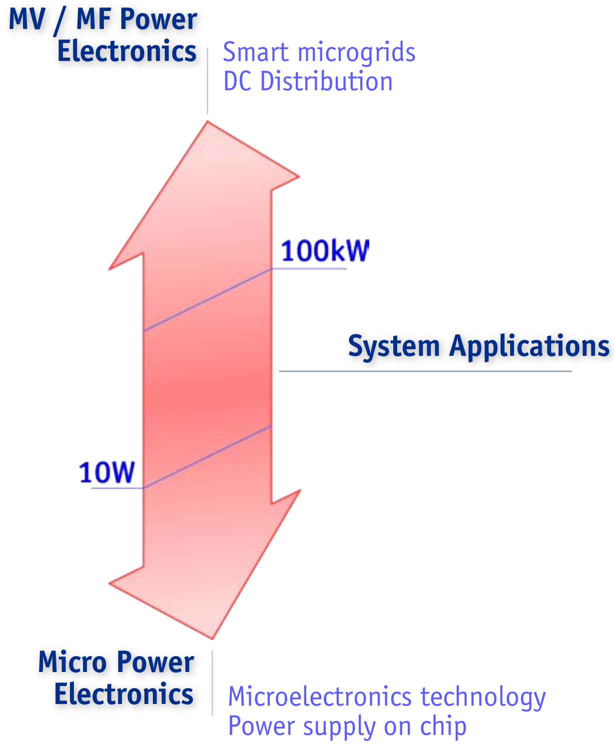
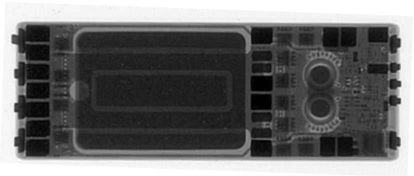






- **Future (Soon):** **Medium Freq. Medium Volt.** Smart microgrids, DC distribution
- **Future:** **Micro Power Electronics** Microelectronics technology, power supply on chip

Today's Measurement Concepts

...in power electronic systems:
Passive components
Active components
System level

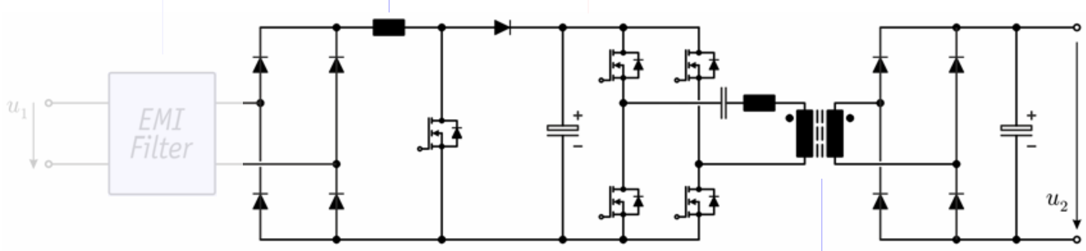
▶ Boost-type PFC with Isolated DC-DC Stage — Revisited

- **Passive Components:** Inductors, transformers, capacitors

Boost Inductor:
- DC-biased core losses
- High-frequency copper losses

EMI Filter:
- Common-mode
- Differential-mode

DC-DC converter switches:
- Soft-switching losses (ZVS/ZCS)



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Isolation Transformer
- Non-sinusoidal core excitation
- Litz wire high-frequency losses

Efficiency

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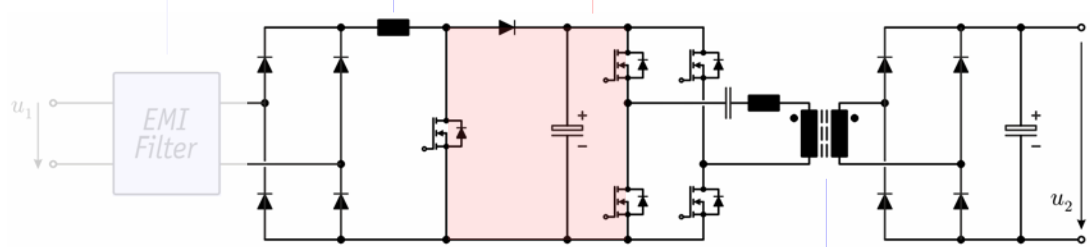

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Efficiency

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- **Passive Components:** Inductors, transformers, capacitors
- **Active Components:** Switches, diodes

- **System Level:** Efficiency, EMI compatibility

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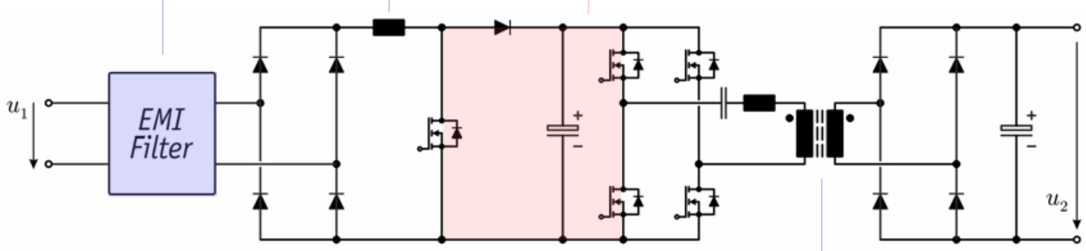

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Efficiency

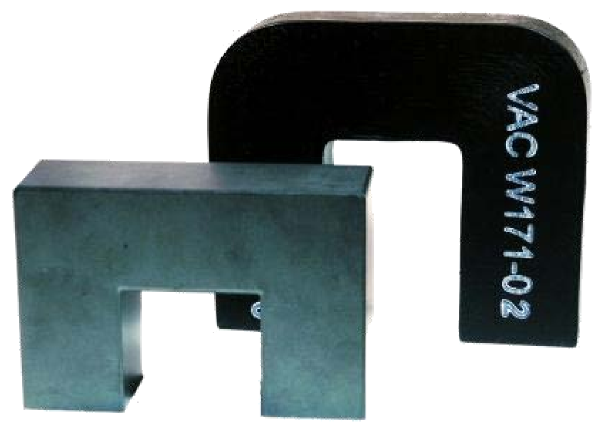
Today's Measurement Concepts

...in power electronic systems:
Passive components
Active components
System level

▶ Measurement of Core Losses

- Datasheet provided parameters are only valid for sinusoidal excitation
- **Differences of up to <u>two times</u> in core losses with respect to calculated values have been reported**

Tape wound core

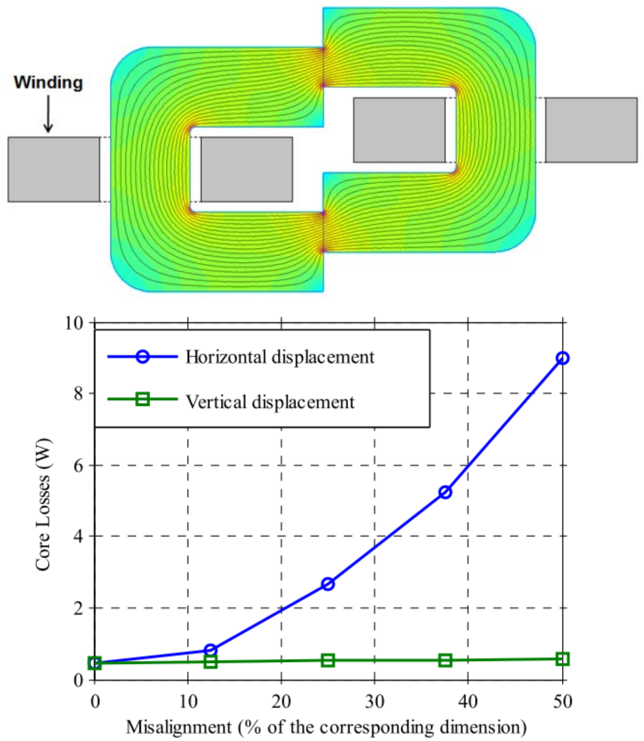


Ferrite core

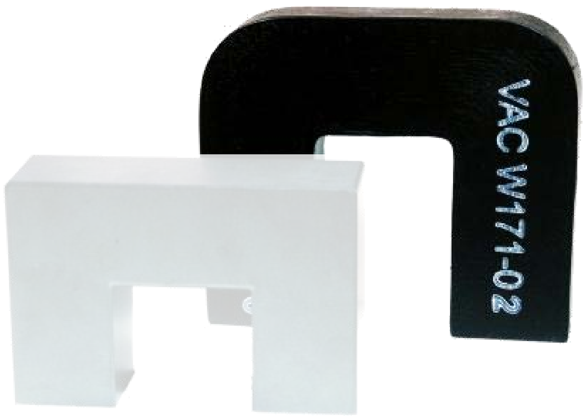
- Improved core loss estimation methods for non-sinusoidal excitation should be considered
- ... or a relatively simple core-loss estimation system can be built.

▶ Measurement of Core Losses

- Increase of core losses due to misalignment of tape wound cores



Tape wound core



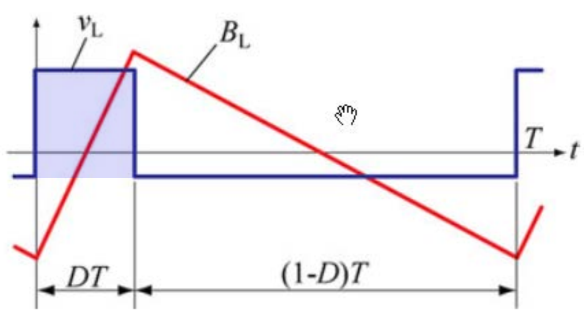
Source: B. Cougo 2011
"Increase of Tape Wound Core Losses due to Interlamination Short Circuits and Orthogonal Flux Components"

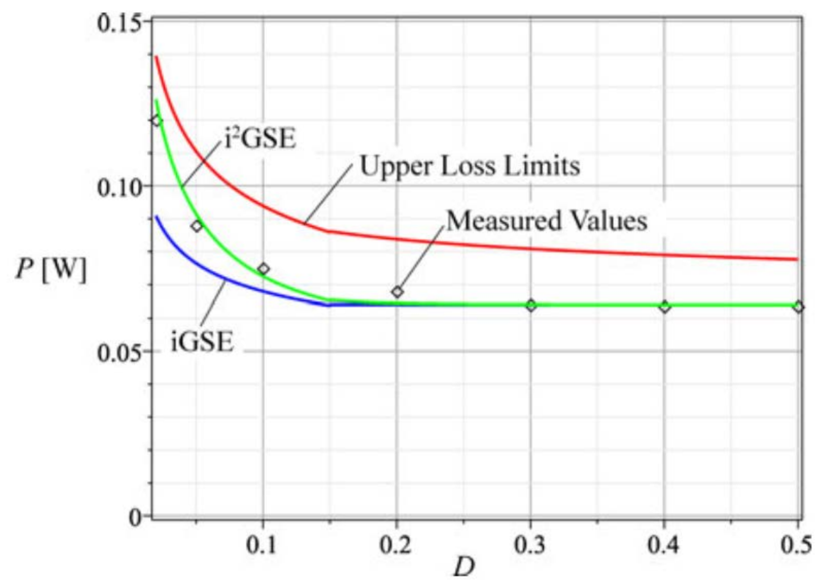
- **Core losses are extremely sensitive to horizontal misalignment**

► Core Loss Measurement Equipment

- Characterization of the core losses in inductor for variable duty cycle
- The losses based on the i²GSE match the measured losses for variable duty cycle

Source: J. Mühlethaler 2012
"Improved Core-Loss Calculation for Magnetic Components Employed in Power Electronic Systems"

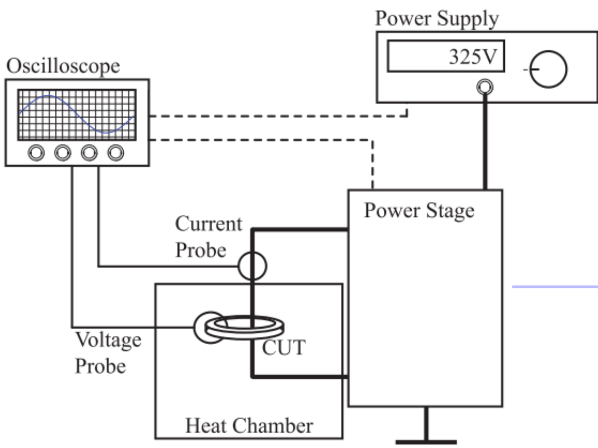




- Improved core loss estimation methods should be used for calculation of core losses in PE circuits
- **A simple testbench can be built in order to characterize core materials for a specific application**

▶ Core Loss Measurement Equipment

- Full-bridge structure generates typical excitations found in power electronic converters
- External power supply adjusts the voltage amplitude



Source: J. Mühlethaler 2010
"Core Losses under DC Bias Condition based on Steinmetz Parameters"

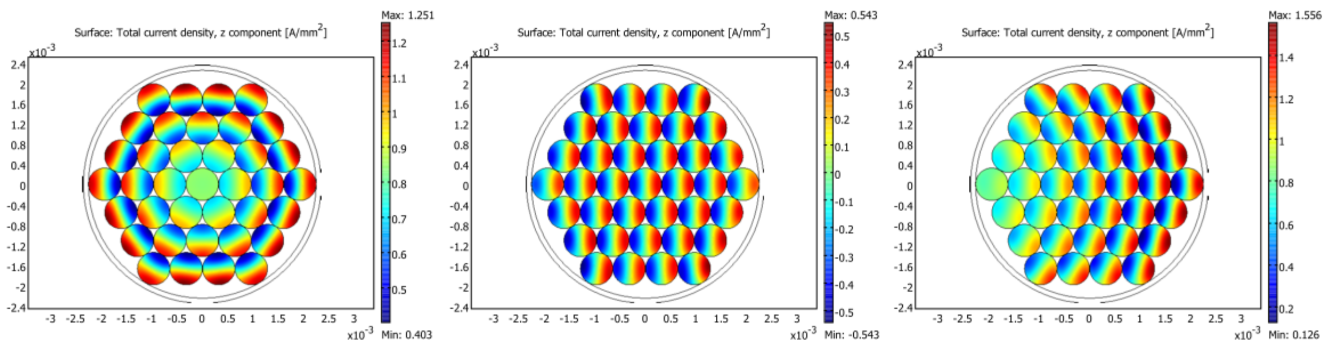
Power stage based on full-bridge structure

- **Voltage and current are measured simultaneously to extract the core's BH loop**

► High Frequency Effects in Copper Conductors

- Skin and proximity effects arise from the conduction of high-frequency currents in copper cond.

Source: I. Villar 2010
"Multiphysical Characterization of Medium-Frequency Power Electronic Transformers"



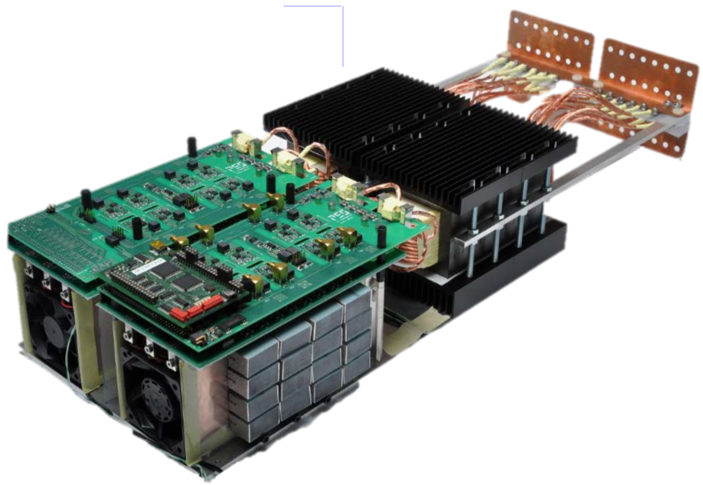
Skin effect | Proximity effect | **Combined**

- **Not accounting for high-frequency effects results in low accuracy in converter loss estimation**
- Manufacturing of high quality litz wire is complex and costly

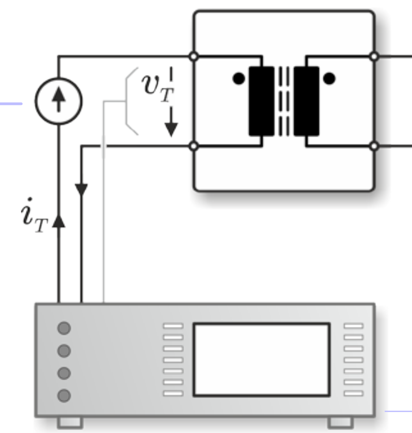
► Copper Loss Measurement Equipment

- The transformer must be short circuited on its secondary terminal with a very low resistive path
- An AC current source provides the high-frequency current with the required RMS value

High-current high-frequency
AC source



Transformer under test



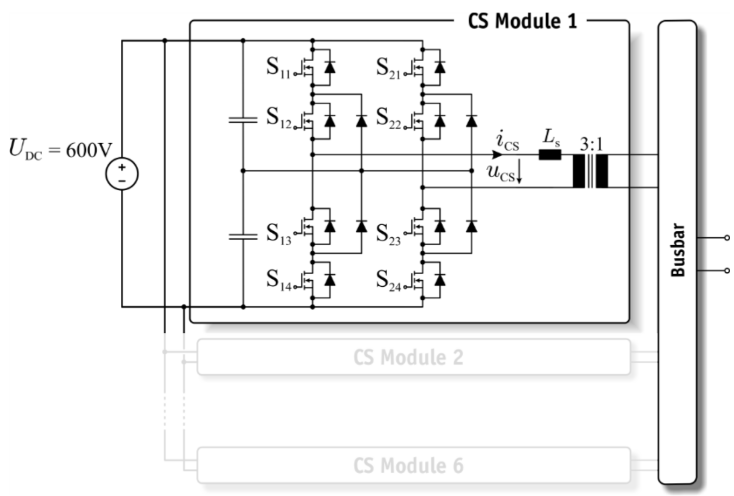
!
Short circuit

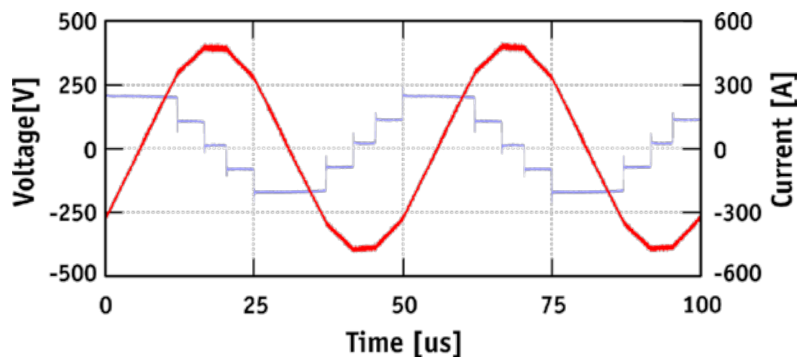
High-precision
power analyzer

- Since the power delivered is manly reactive a high power analyzer is utilized to measure the total losses

▶ Copper Loss Measurement Equipment

- The current source: 5-level NPC bridges feeding an inductive load through a step-down transformer
- Mid-point voltage balancing required for stable operation



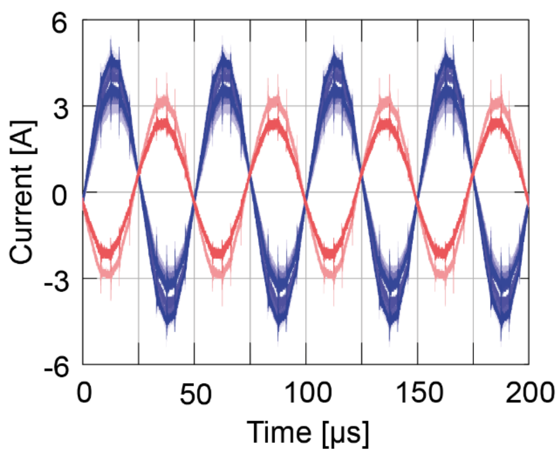


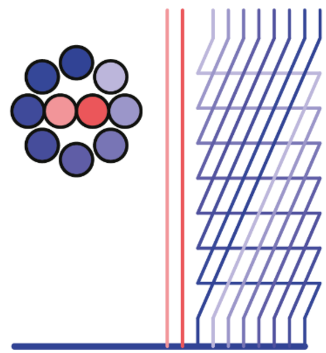
Source: Ch. Gammeter 2012
"Medium Frequency High Current Source for Testing Interconnections in High-Power Converters"

- **Minimum THD modulation achieves low harmonic distortion in output current**

► Copper Loss Measurement — Litz Wire Bundles

- Case study: Litz wire (tot. 9500 strands of 71μm each) with 10 sub-bundles
- Current distribution in internal litz wire bundles depends strongly on interchanging strategy





Source: G. Ortiz 2013
"Medium Frequency Transformers for Solid-State Transformer Applications — Design and Experimental Verification"

10 bundles 950 with 71μm strands each

- Total copper losses for 10 bundles: 438W

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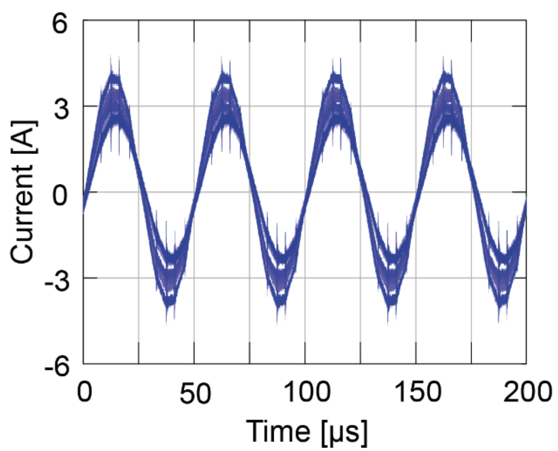
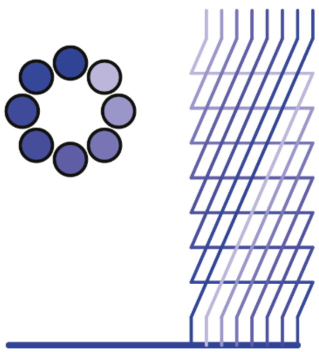




Source: G. Ortiz 2013
"Medium Frequency Transformers for Solid-State Transformer Applications — Design and Experimental Verification"

10 bundles 950 with 71µm strands each

- Total copper losses for 10 bundles: 438W
- **Total copper losses for 8 bundles: 353W**

Today's Measurement Concepts

...in power electronic systems:
Passive components
Active components
System level

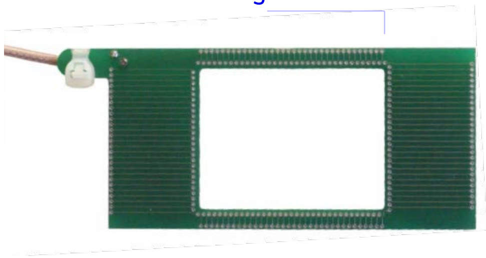
▶ Switching Loss Measurement — Current Sensing

- High bandwidth (tens of MHz) and (in most cases) isolated transducer

- Current transformer
- Rogowski coil (PCB)

Rogowski coil
Source: www.pemuk.com

PCB Rogowski coil



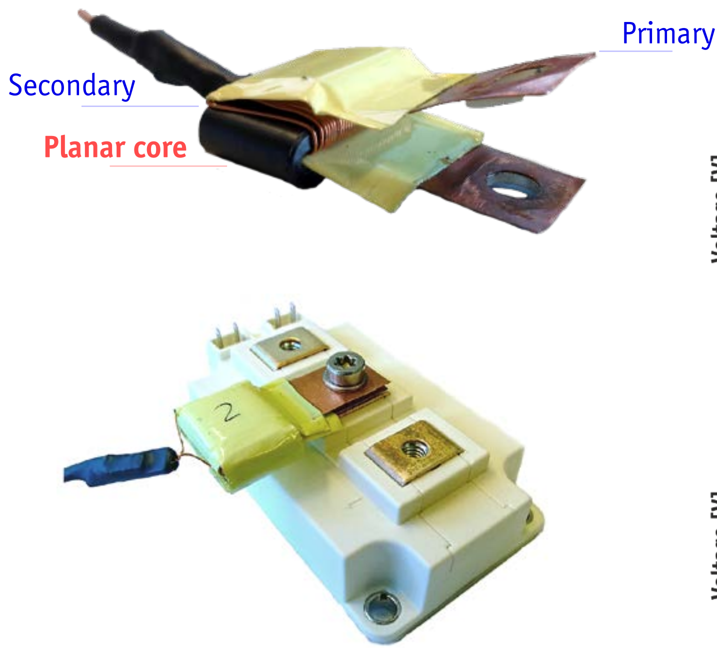
Planar current transformer

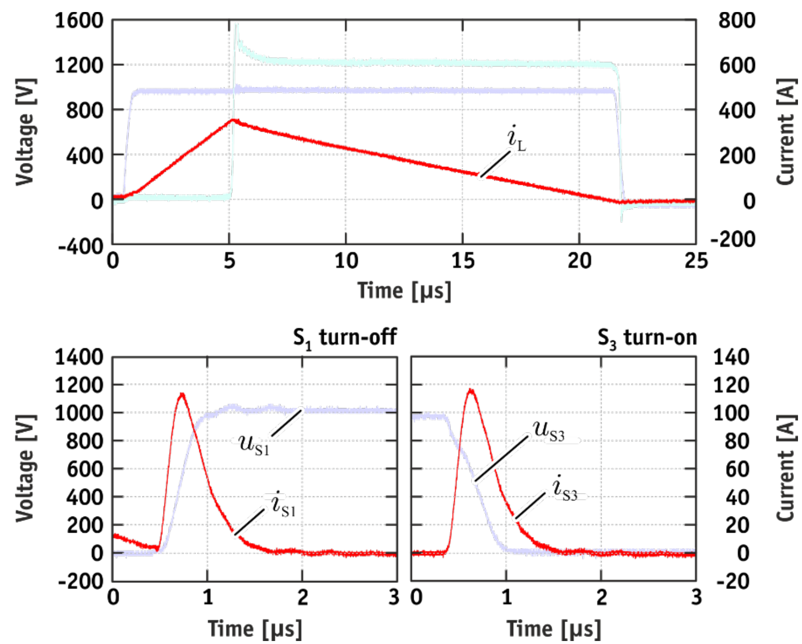
Coaxial current shunt
Source: www.ib-billmann.de

- **High bandwidth coaxial current shunt (expensive, non-isolated)**

▶ Switching Loss Measurement — Current Sensing

- Current transformers:
  - High bandwidth isolated planar current transformer built in-house with standard components
  - Designed for pulse operation → small construction





- Very easy to manufacture!

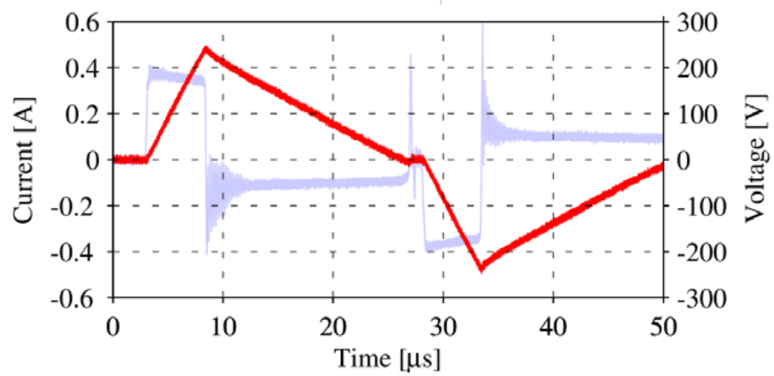
▶ Switching Loss Measurement — Current Sensing

- Rogowski Coils

- High bandwidth, isolated Rogowski coil built with standard PCB
- For switching loss measurement, the integration is preferably done in post-processing

PCB Rogowski coil placed on an IGBT module

Resulting voltage output and **integrated signal**



Source: Y. Lobsiger 2011
"Decentralized Active Gate Control for Current Balancing of Parallel Connected IGBT Modules"

- Extremely low effect on power circuit
- **Very well suited for measurement in IGBT modules**

► Switching Loss Measurement — Current Sensing

- Current shunt
- Exceptionally high bandwidth (in the GHz range) and direct voltage output
- PCB soldered shunts offer the possibility to measure switches with virtually any package

Coaxial current shunt
Source: www.ib-billmann.de

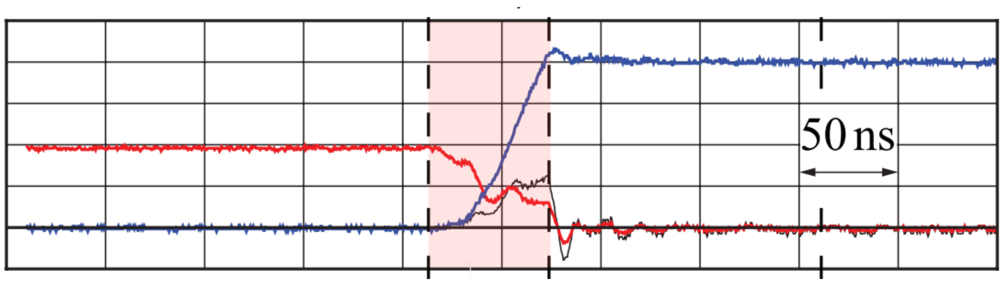
Source: R. Burkart 2013
"Comparative Evaluation of SiC and Si PV Inverter Systems Based on Power Density and Efficiency as Indicators of Initial Cost and Operating Revenue"

- Typically expensive and non-isolated → **requires an oscilloscope with isolated channels**
- Alternative constructions with SMD resistors also possible

► Switching Loss Measurement — Deskew

- MOSFET and SiC technology feature ultra high switching speeds in the tens of nanoseconds range
- Light takes about 3.3ns to travel 1 meter → different cable lengths can lead to meas. inaccuracies

1.7kV SiC JFET turn-off:
drain current
drain-source voltage



Source: R. A. Friedemann 2012
"Design of a Minimum Weight Dual Active Bridge Converter for an Airborne Wind Turbine System"

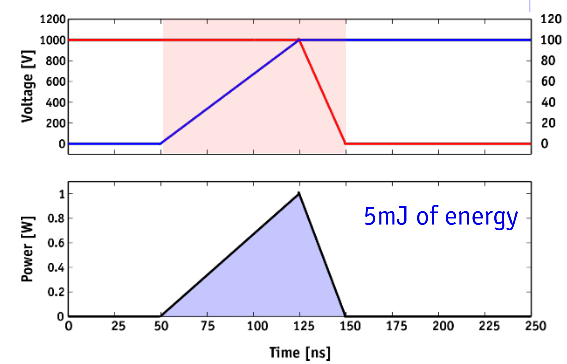
- **Specially critical if the voltage/current measurement is not done passively (e.g. diff probes)**

▶ Switching Loss Measurement — Deskew

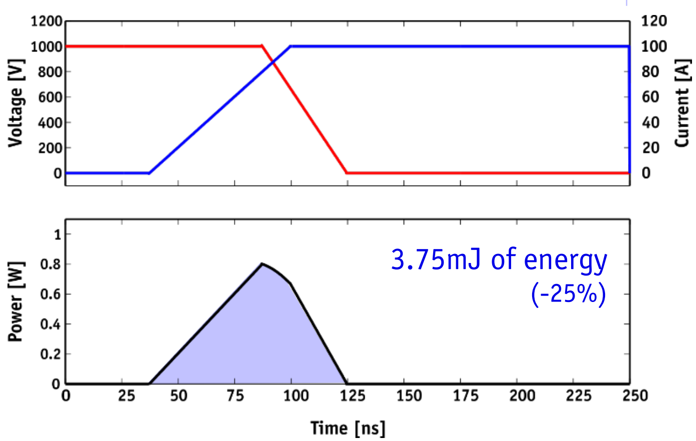
- Simplified example case:

- Switching 100A with a 1000V DC-link
- Unipolar-type semiconductor, i.e. **no tail current** with a **linear parasitic capacitance** and ideal circuit layout (no parasitic stray inductance, hence **no switching overshoot**)
- Switching time: 100ns

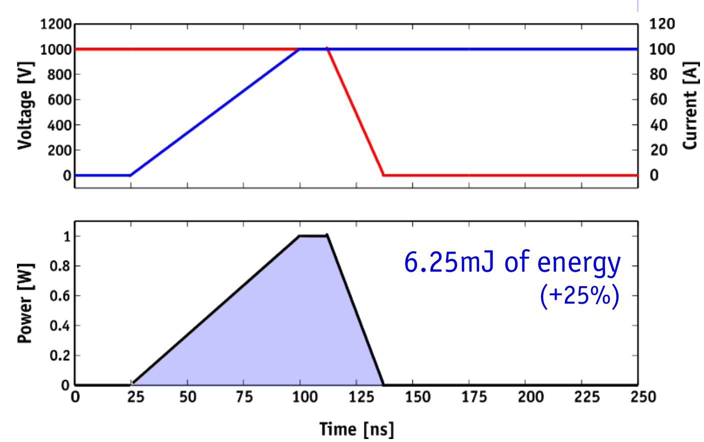
Nominal



Voltage lagging 12ns



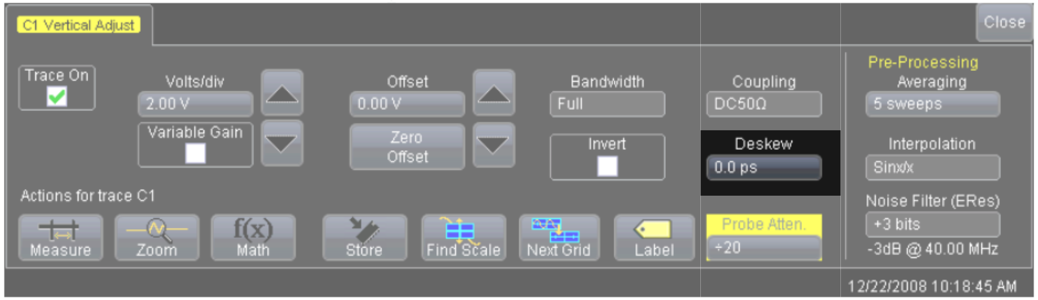
Current lagging 12ns



- **Deviations of ±25% on measured energy with only a 12ns deskew**

▶ Switching Loss Measurement — Deskew

- Correcting deskew mismatch can be done directly in modern oscilloscopes
- Example: Lecroy Wavesurfer MXs-B oscilloscope



Source: www.teledynelecroy.com

- Or in post-processing (e.g. with Matlab)
- **In all cases, the deskew must be properly measured beforehand**

Today's Measurement Concepts

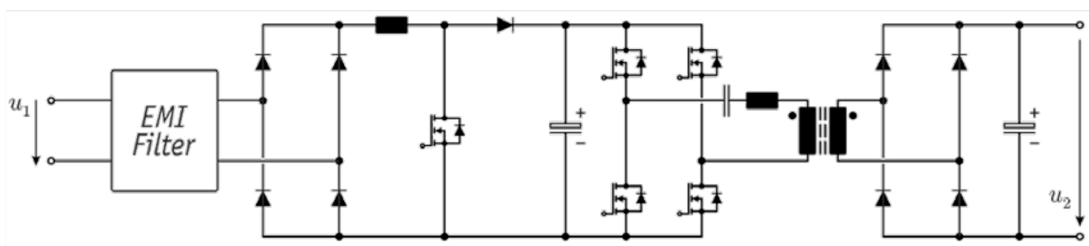
...in power electronic systems:
Passive components
Active components
System level

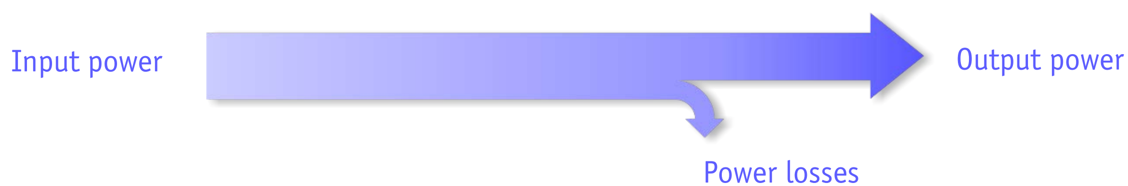
▶ Assessing System's Performance — Efficiency

- Efficiency constitutes one of the systems primary performance indices
- The measurement of efficiency is typically done in one of two ways:

- Measurement of input and output power
- Measurement of input <u>or</u> output power and power losses

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{loss}}$$





- The desired accuracy of the efficiency measurement will determine which method should be used

▶ Assessing System's Performance — Efficiency

- Input and output power measurement

- **Power analyzer:** **Yokogawa WT3000**
- Reading accuracy: 0.02%
- Range accuracy: 0.04%

www.yokogawa.com

- **Table multimeter:** **Agilent 34401**
- Reading accuracy: 0.005% @ 100mV
- Range accuracy: 0.0035% @ 100mV

www.agilent.com

Source: Th. Schröter 2011
"Aspects and Considerations for Accurate Measurement of Very High Efficiency"

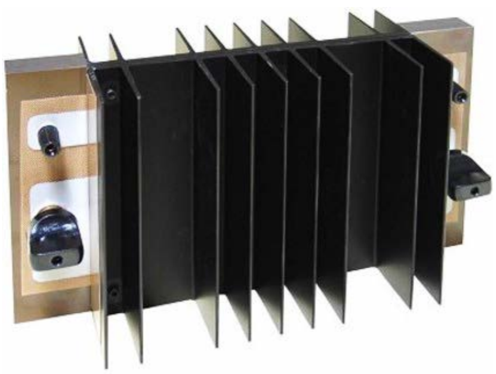
▶ Assessing System's Performance — Efficiency

- Input and output power measurement

- **Handheld multimeter:** **Fluke 80 series V**
- Reading accuracy: 0.3% @ 600mV

www.fluke.com

- **Shunt resistor (curr. meas.):** **Burster 1282**
- Shunt resistance: 1mΩ (1mV/A)
- Resistance tolerance: 0.02%
- Temperature coefficient: 0.001 %/°K

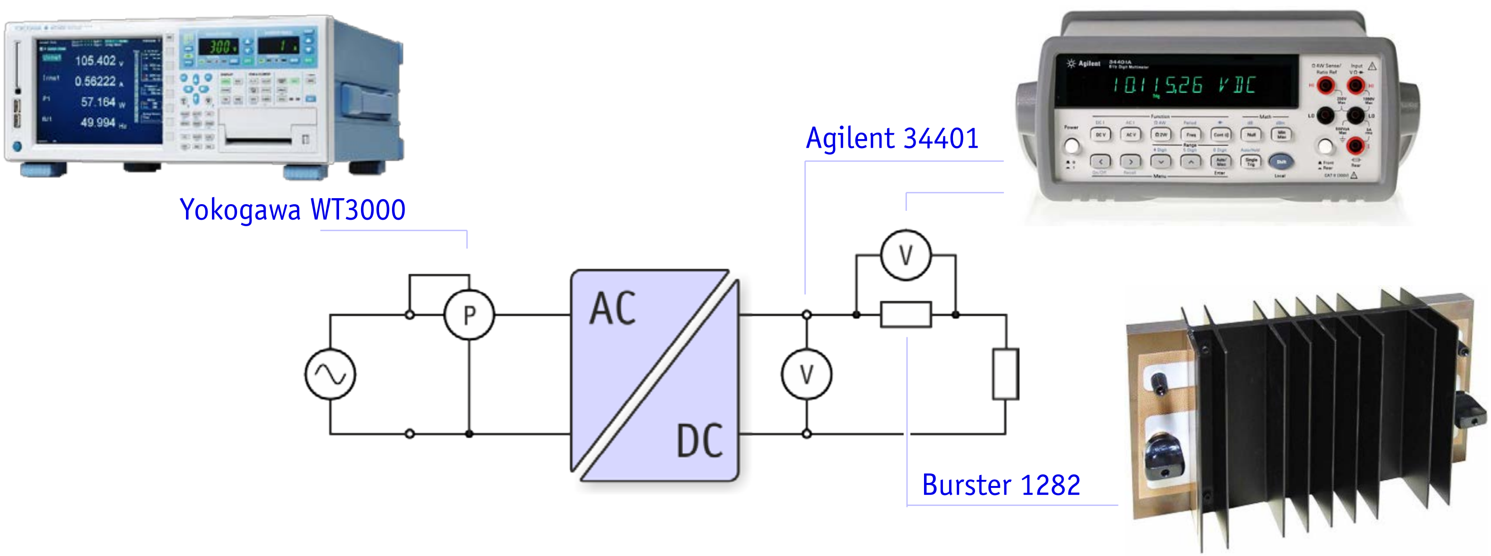


www.burster.com

Source: Th. Schröter 2011
"Aspects and Considerations for Accurate Measurement of Very High Efficiency"

▶ Assessing System's Performance — Efficiency

- Measurement situation example:
- Input power (AC side): **Yokogawa WT3000**
- Output power (DC side): **Agilent 34401 (voltage)**
  Burster 1282 & **Agilent 34401 (current)**

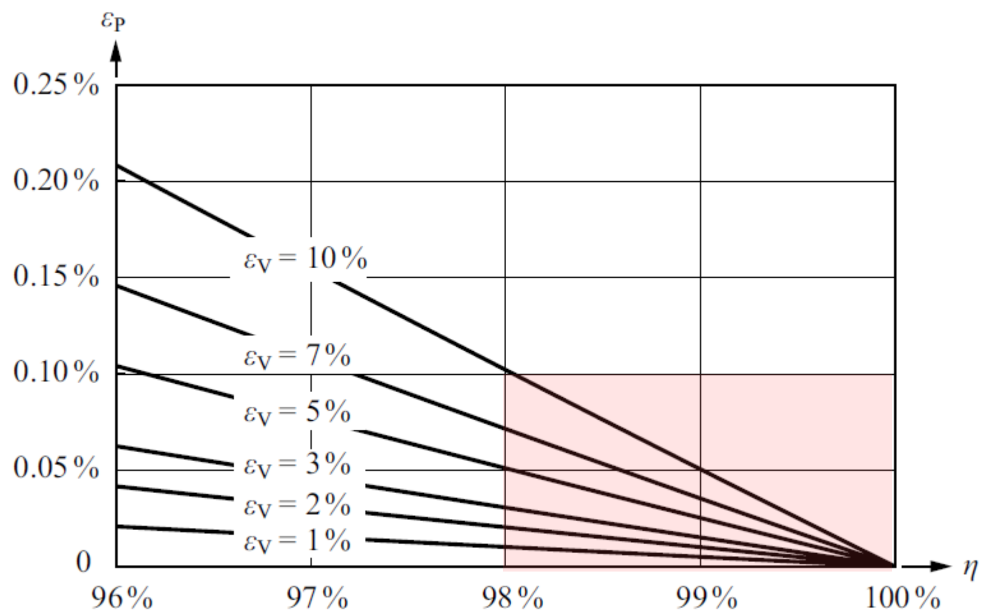


Source: Th. Schröter 2011
"Aspects and Considerations for Accurate Measurement of Very High Efficiency"

- **Achieved power measurement accuracy: ±0.107%**

▶ Assessing System's Performance — Efficiency

- Maximum permissible relative error in the power measurement for the determination of the losses with a max. relative error of in dependence on the efficiency

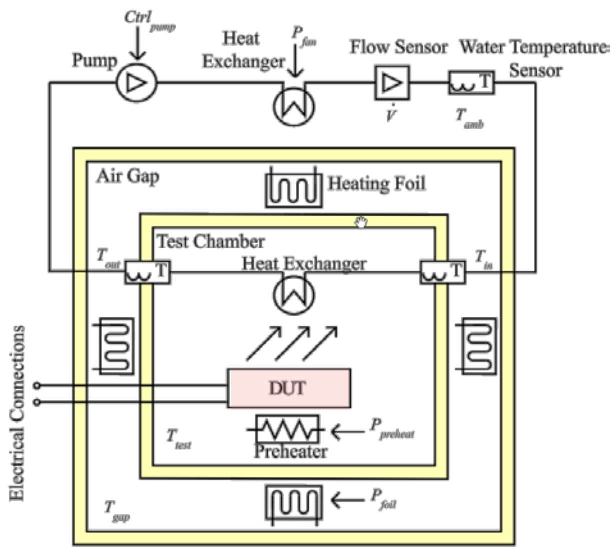


Source: J.W. Kolar 2012
"Extreme Efficiency Power Electronics"

- **The power measurement accuracy must be extremelly high when an accurate efficiency meas. is desired**

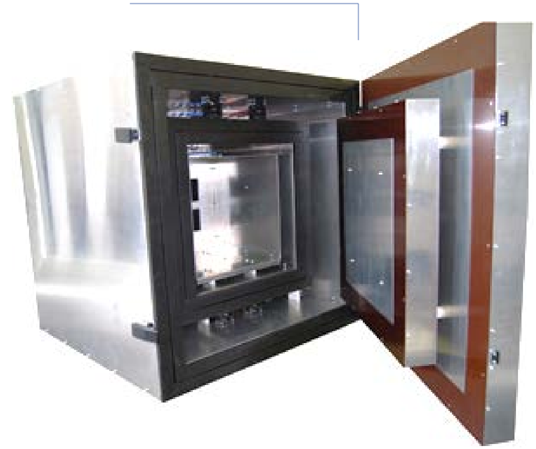
▶ Assessing System's Performance — Efficiency

- **Calorimetric direct power loss measurement**
- Converter placed in a controlled-temperature double-jacketed chamber
- A water-cooled heat exchanger extracts the heat generated by the converter
- The power extracted through the water-cooling circuit corresponds to the losses gen. by the conv.



Source: D. Christen 2010
"Calorimetric Power Loss Measurement for Highly Efficient Converters"

Calorimeter manufactured by enertronics GmbH

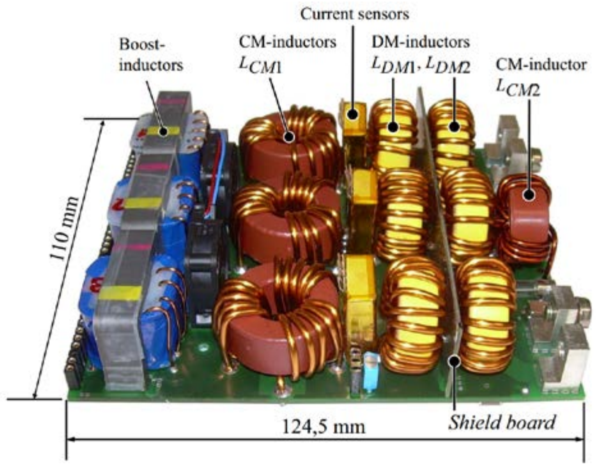


www.enertronics.ch

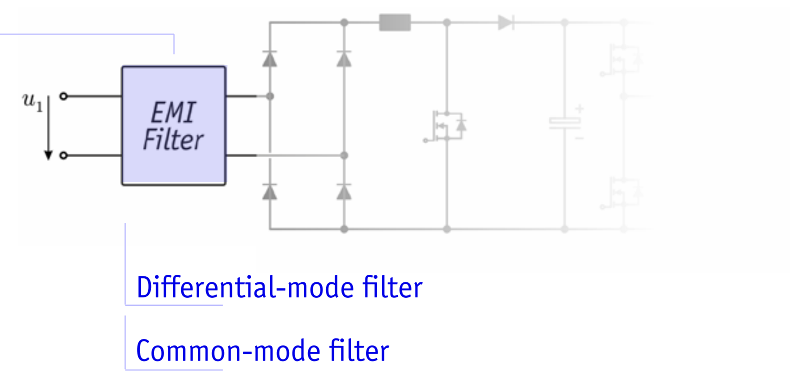
- **Accuracy higher than ±1W up to 100W of losses (e.g. for a 1kW converter → ± 0.1% accuracy)**

▶ Assessing System's Performance — EMI Compatibility

- The performance of the EMI filter is split into:
- Differential-mode rejection and
- Common-mode rejection



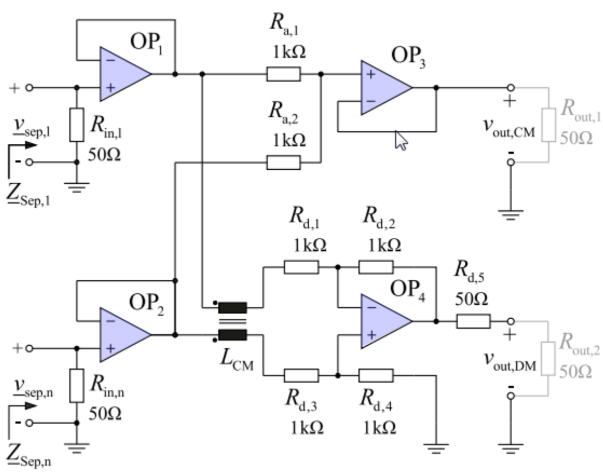
Source: M. Hartmann 2010
"EMI Filter Design for High Switching Frequency Three-Phase/Level PWM Rectifier Systems"

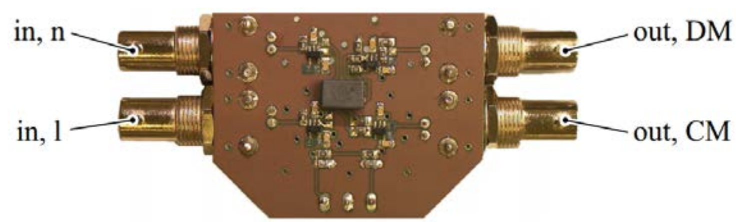


- **These two parameters must be separated by a dedicated circuit**
- This allows to identify and correct possible incompatibilities with the respective EMI directives

► Assessing System's Performance — EMI Compatibility

- Simple active circuit for separation of CM and DM noise
- Requires 4 OP-amps and passive components





Source: S. Schroth 2014
"Analysis and Practical Relevance of CM/DM EMI Noise Separator Characteristics"

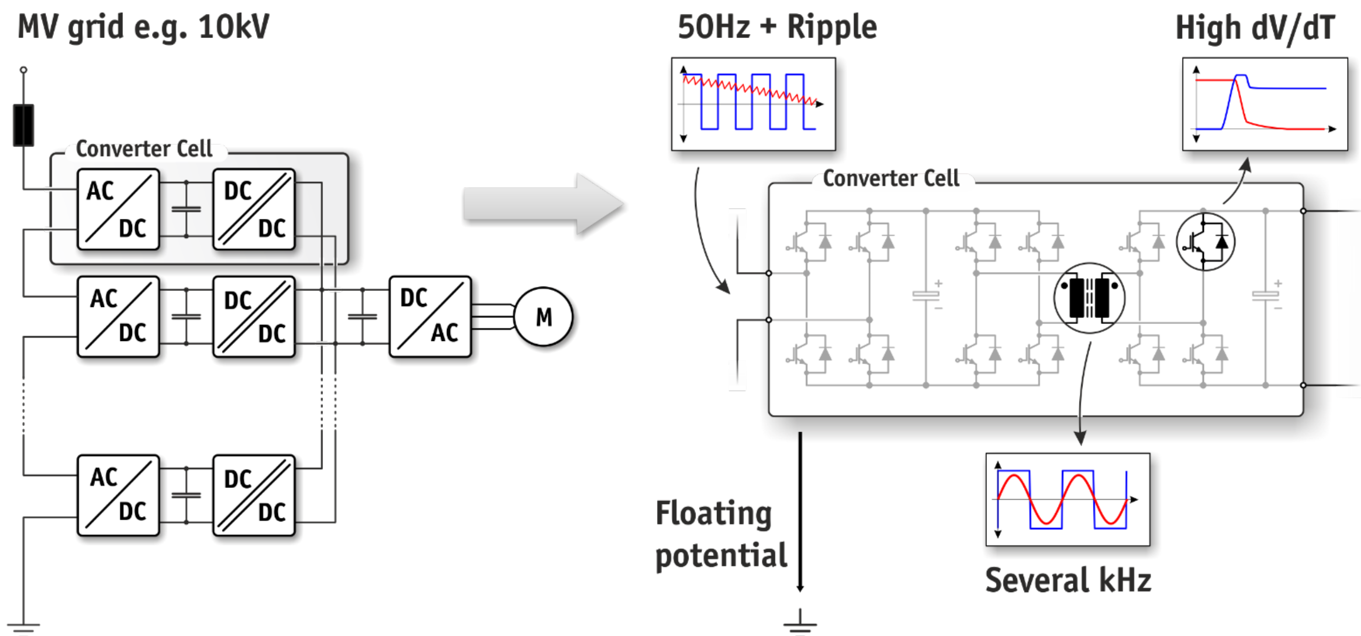
- **Achieves DM_{TR}/CM_{RR} > 51 dB and CM_{TR}/DM_{RR} > 47dB for frequencies up to 10MHz**

Future Technologies

Smart Grid / DC Distribution
Highly Integrated Microelectronics

► Future Traction Vehicles Based on SST Technology

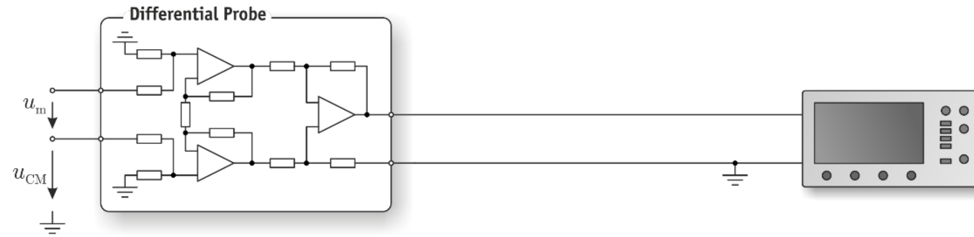
- Typical measurements performed during testing and commissioning of power electronic converters



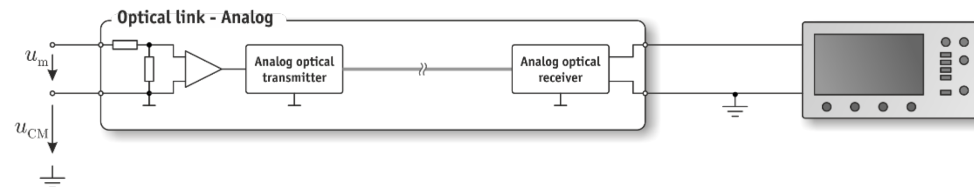
- **Floating potentials:** **Up to tens of kilovolts and tens of kilovolts/microsecond**
- Voltages / currents: From millivolts to kilovolts, from amps to kiloamps, **DC to tens of MHz**

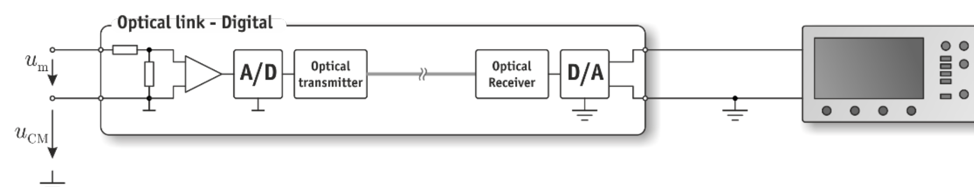
▶ State-of-the-Art Isolated Voltage Measurement

- Basic types
  - Differential probes



  - Optically isolated systems (analog link / digital link)

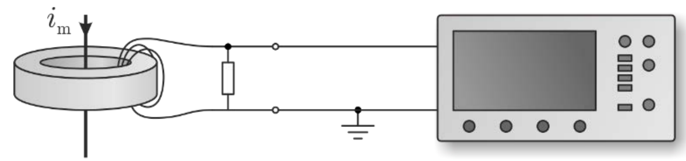




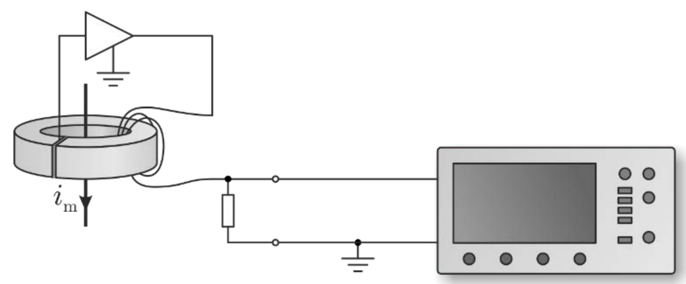
- Drawback: probe combines isolation and measurement

▶ State-of-the-Art Isolated Current Measurement

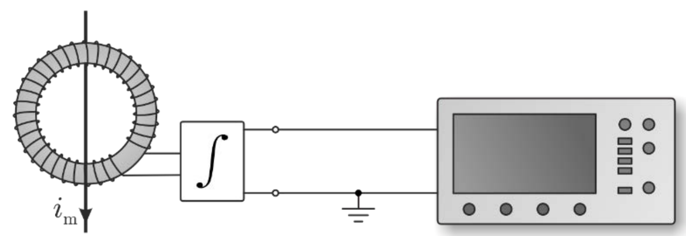
- Basic types
  - Current transformers



  - Current compensated transformers (clamp-on current probes)



  - Rogowski coils

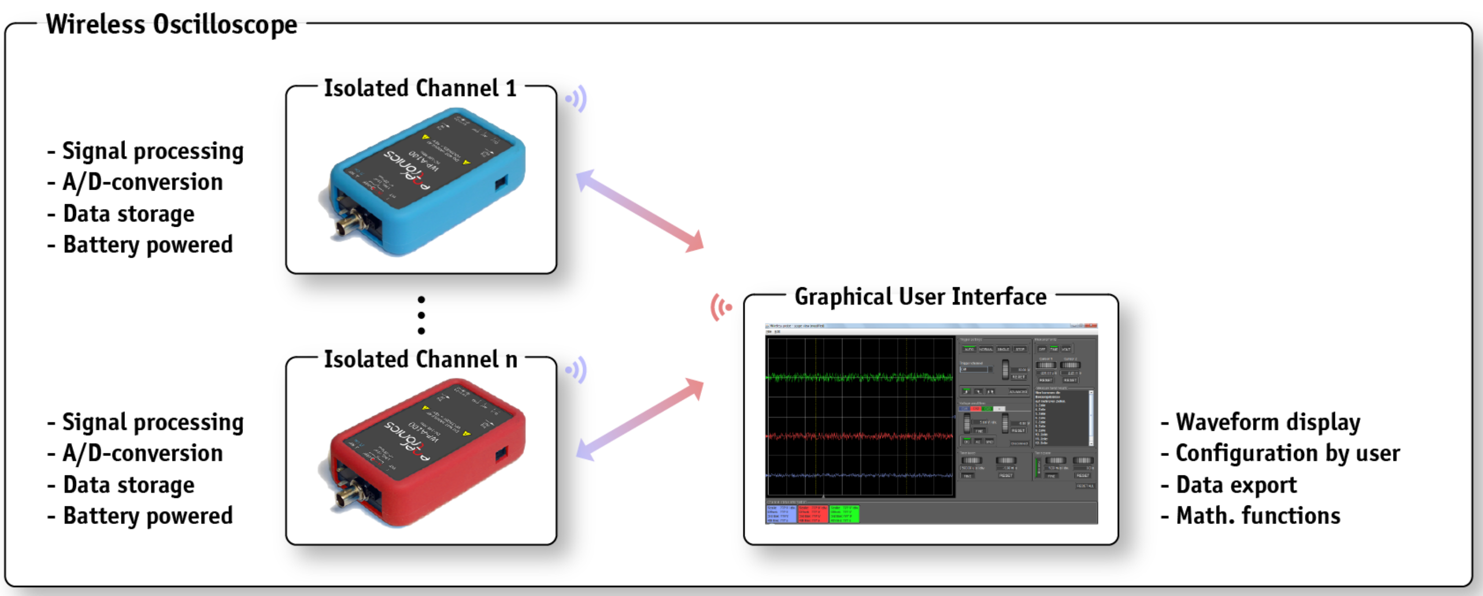


- **Drawback: combination of isolation and measurement**

▶ Wireless Oscilloscope – Basic Idea

- Provide the isolation at a different position in the measurement chain

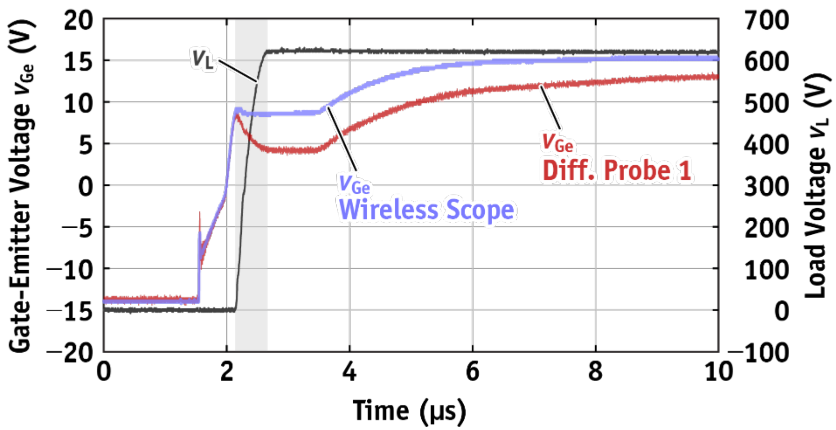
- Separate data acquisition (channels) and user interface
- No need for isolated probes / sensors
- No need for an additional oscilloscope

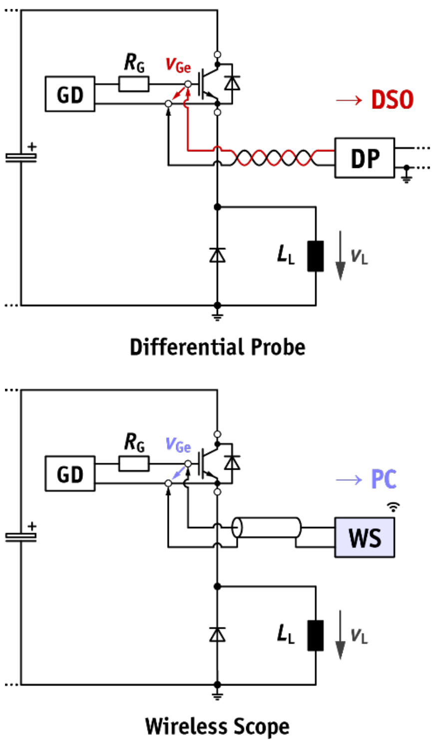


- System overview of a 100MHz wireless channel oscilloscope

▶ Isolated Voltage Measurement

- Setup consist of measurement of high side gate signal on a half-bridge-type structure
- The differential probe exhibits strong CM error during high dv/dt





- The Wireless Scope feautres no visible CM error

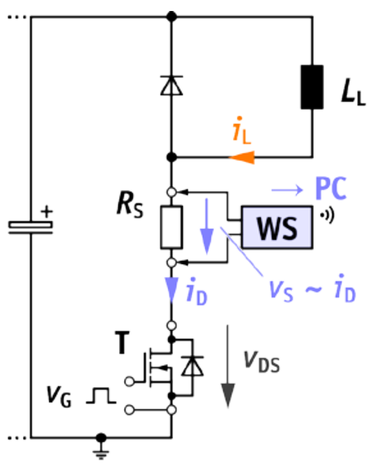
▶ Isolated Current Measurement

MOSFET drain current

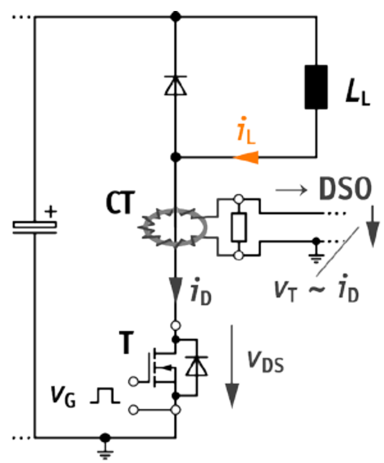
- Floating reference voltage
- High bandwidth current transients (turn-on / turn-off)

Measurement setup

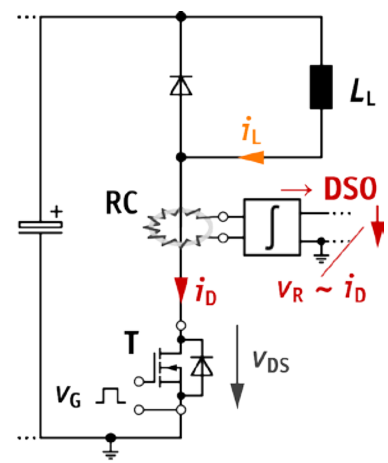
- 0.1 Ohm shunt & Wireless Scope
- Current transformer
- Rogowski coil



Shunt & Wireless Scope

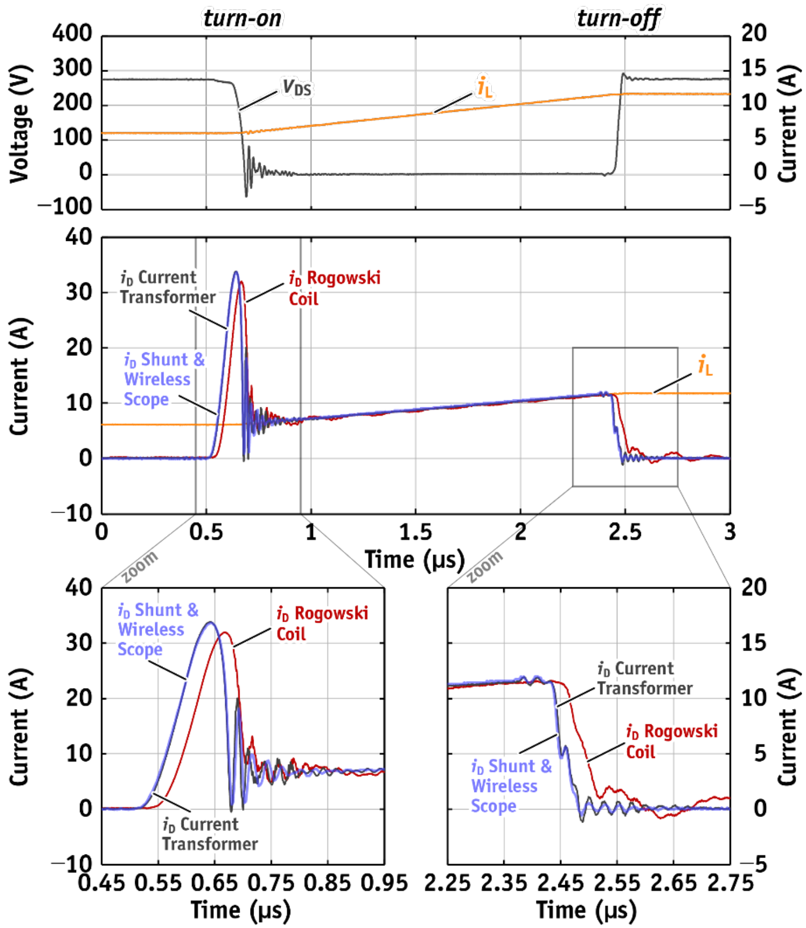


Current Transformer



Rogowski Coil

► Isolated Current Measurement 2 — Results



Rogowski Coil

- Delay
- Limited bandwidth
- Ringing due to CM transients
- Limited isolation voltage

Current Transformer

- High bandwidth
- No apparent CM error
- High-pass characteristic (no DC)
- Limited isolation voltage

Shunt & Wireless Scope

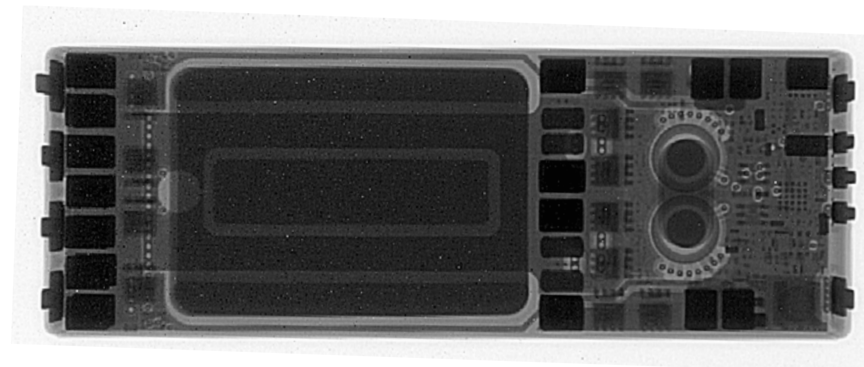
- High bandwidth
- No apparent CM error
- DC – 100 MHz
- No intrinsic limitation on isolation voltage

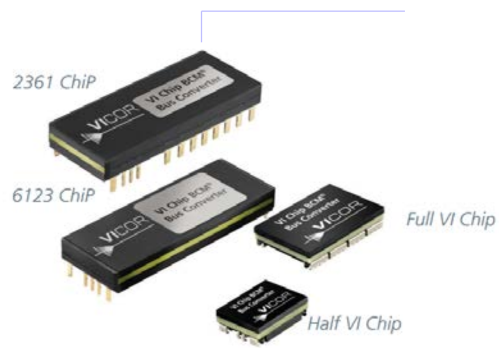
Future Technologies

Smart Grid / DC Distribution
Highly Integrated Microelectronics

► Example Microelectronics Highly Integrated Converter

- Isolated (4kV) DC-DC converter with power output up to 1.7kW

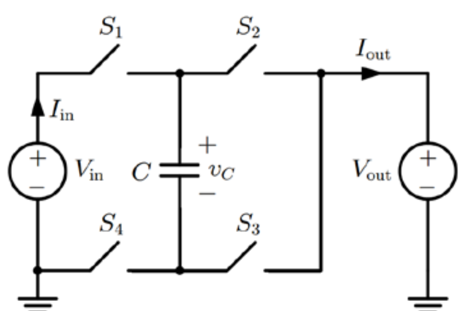


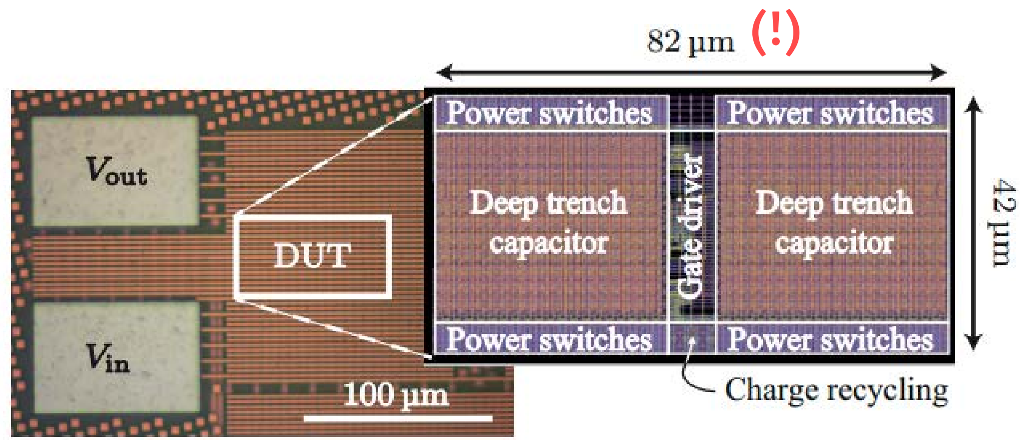


- How to test the circuit? How to measure internal signals? How to characterize switching performance? How to characterize magnetics performance?

▶ Example of Power Supply on Chip

- Switched capacitor converter with 4.6W/mm² and 86% efficiency





Source: T. Andersen 2013
"A 4.6 W/mm2 Power Density 86% Efficiency On-Chip Switched Capacitor DC-DC Converter in 32nm SOI CMOS"

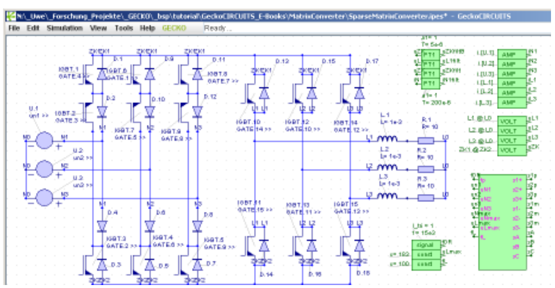
- How to test the circuit? How to measure internal signals? How to characterize switching performance? How to characterize capacitor performance?

▶ Future Micro Power Electronic Solutions

- Merge simulation and measurement to create a "simulation-augmented" environment

Simulation model

Measurement quantities

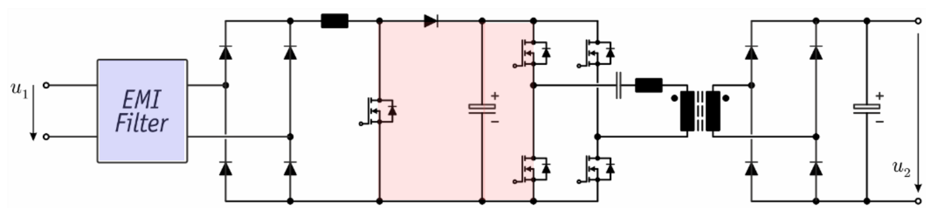


- **Link between these two enables to supervise internal quantities of the experimental hardware**

Summary / Outlook

▶ Measurement in Today's Power Electronics

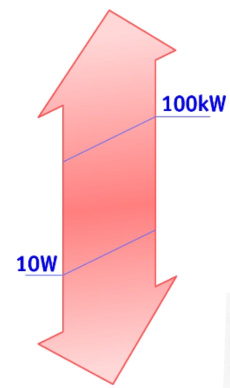
- **Design of power electronics circuit that fulfills given specifications**
  - Components: Passives, Actives
  - System: Efficiency, EMI

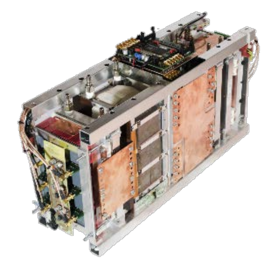


▶ Measuring Future Power Electronics

- **High-power medium-frequency electric power systems-oriented**
  - High common-mode, high isolation, high bandwidth
  - Wireless measurement systems

- **Microelectronics, highly integrated solutions:**
  - Simulation augmented measurement concepts





Thank You!

Questions?