Power Loss Measurements with Triangular Flux Excitation

Custom Integrated Power Management Solutions

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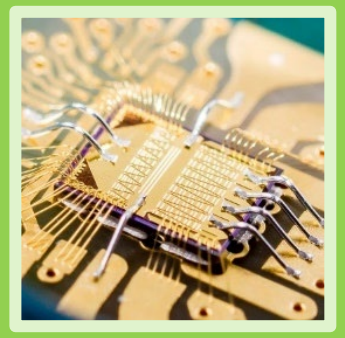
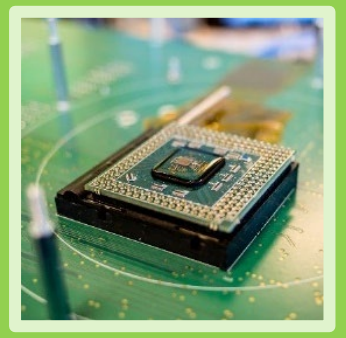
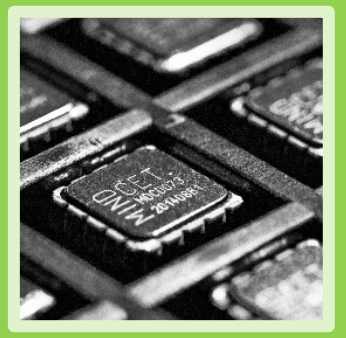
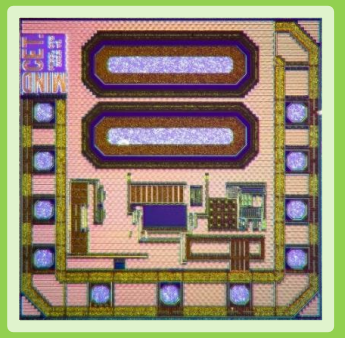
APEC2023 Industry Sessions PSMA



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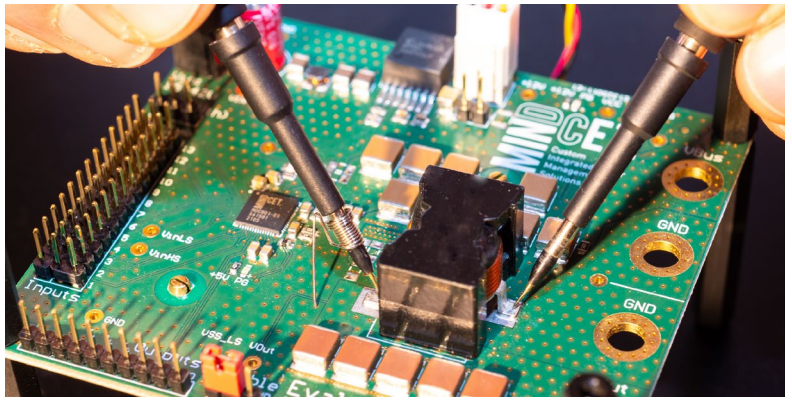
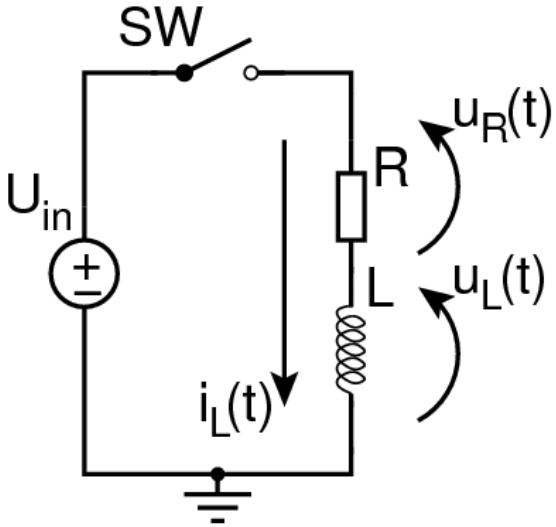
- Outlook
- Conclusions

SMPS Inductors: What do you want to know?

Inductor types and model

- Many types exist, all with their own properties:
  - Magnetic material
  - Geometry
  - Wound / single wire
  - Round / flat wire
  - …





- Basic models incorporate L, Rdc, Isat @ Idc.
- These are measured using (small signal) sine wave excitation

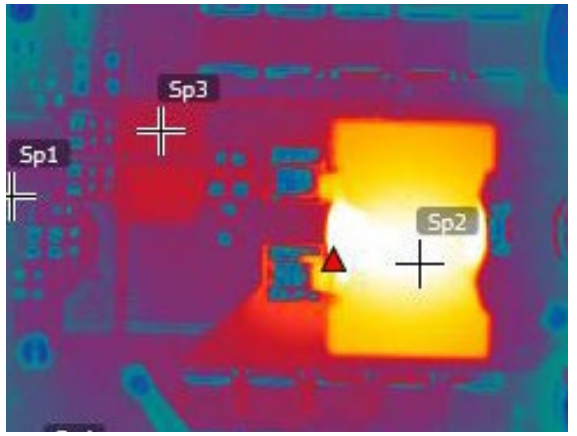
  -> This is not representative for SPMS use!

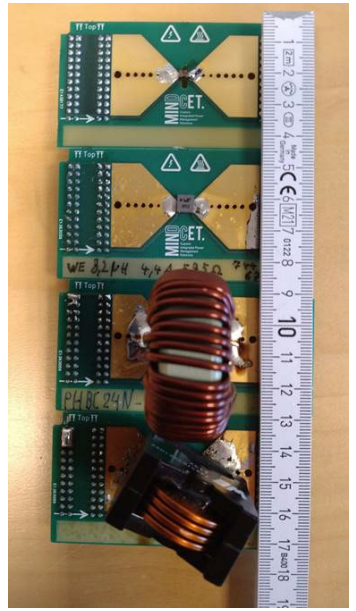
- What about AC losses (winding & core), self-heating, non-linear behavior, handling large triangular currents…?

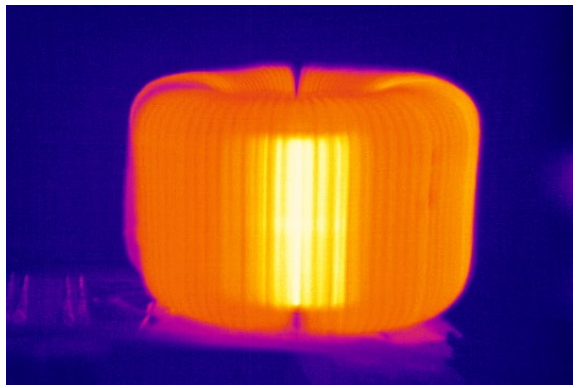
SMPS Inductors: What do you want to know?

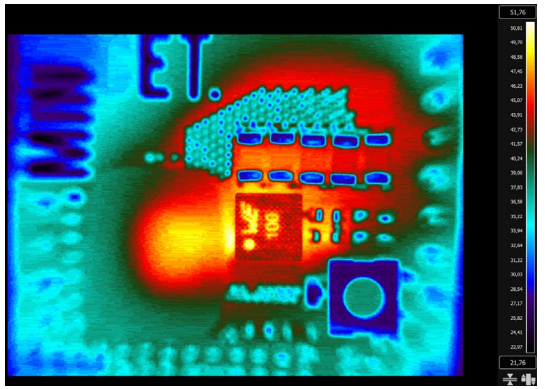
Applications are getting more challenging

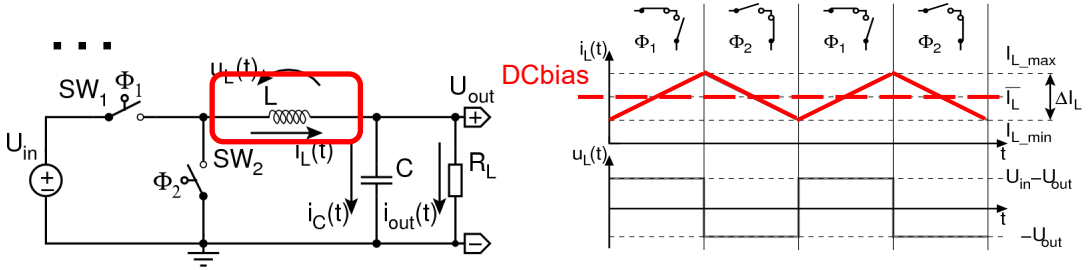
- Higher frequencies
- Higher currents
- Higher power densities
- Wide-bandgap switchers with high dv/dt (GaN & SiC)
- Higher power densities
- …







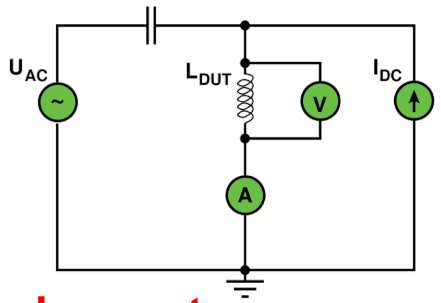




Measuring Inductors

Standard measurement

- Apply a (small signal) continuous sine wave voltage and analyse amplitude and phase shift of the current.
- Optionally, a DC-bias current can be added.
- Use modified Steinmetz to calculate core loss



$$P_v = K_0 \times f_e^{K_f - 1} \times B_{pk}^{K_b} \times f_o$$

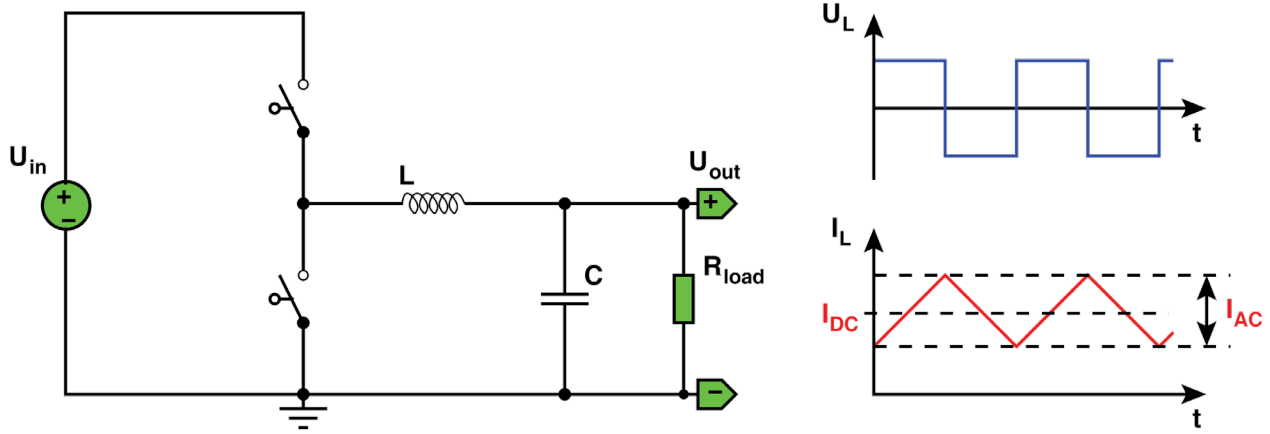
⇒Sine wave is not representative for the application

⇒Need a triangular current with varying DC bias voltage, frequency and duty-cycle to include losses

Triangular Flux: The MADMIX Approach

The principle

- Buck converter where the output inductor is L.U.T.
- Large in/output capacitors create an quasi ideal square-wave voltage source
- The result is a **Triangular Flux Exitation** with adjustable DC-bias, duty-cycle and frequency

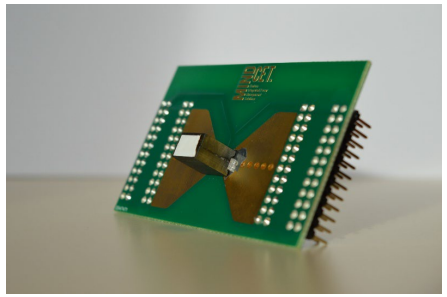


$$I_{rip} = \frac{U_{source}\,\delta\,(1-\delta)}{f_{switch}\,L}$$

Triangular Flux: The MADMIX Approach

The Hardware

- Fully Automated through software
- Thermostreamer to heat or cool the C.U.T. -45 to +225°C
- Calibrated using Calorimetric techniques by compareing AC self heating with a known heating power



Triangular Flux: The MADMIX Approach

Key Measurements

- L = Average inductance over one period
- R_{dc} = DC series resistance
- R_{ac} = Equivalent AC series resistance
- P_{AC} = Total AC power loss
- P_{CORE} = Power loss due to core
- P_{WIND} = Power loss in the windings
- T = Temperature of the L.U.T.

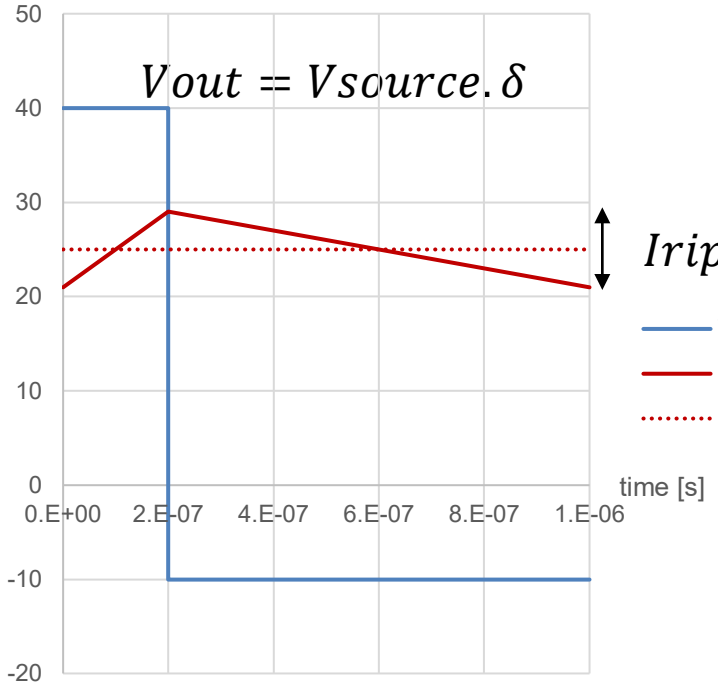
Triangular Flux: AC-power Loss

Energy Balance = AC loss

MADMIX = BUCK converter

example measurement:

- input (=set)
  - source voltage: 50V
  - frequency: 1MHz
  - duty cycle: 20%
  - load current: 25A
- result (=BUCK converter)
  - Vout=10V
  - Irip=8A
- measured & calculated in SW
  - basics: *L, Irip, Iout, Vout, …*
  - bower loss: *Pdc, Pac, Pcore, …*
  - *BH-loop, temperature, …*



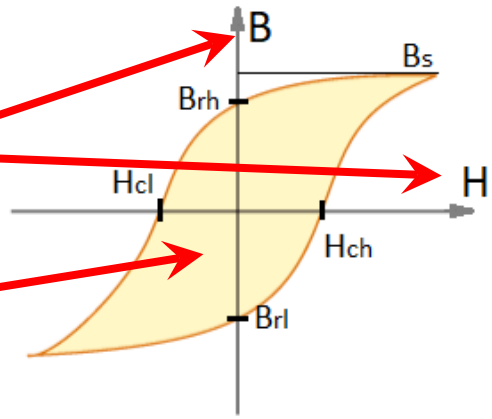
$$Irip = \frac{Vsource.\delta(1-\delta)}{f.L}$$

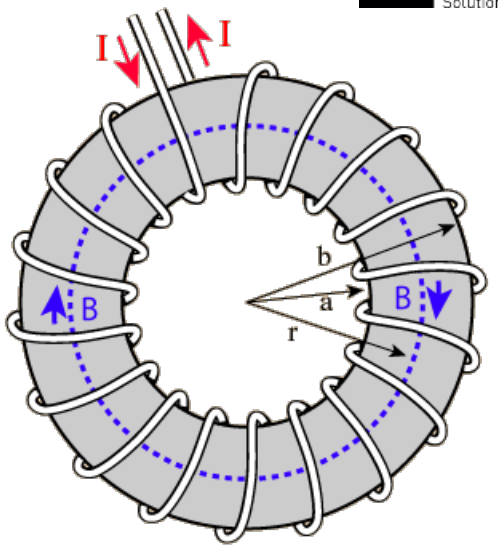
$$Pac = \frac{1}{T}\int_0^T v(t)i(t)dt$$

Triangular Flux: AC-power Loss

Splitting AC-loss into Core and Winding loss

- AC-loss: $P_{ac} = \frac{1}{T}\int_0^T i(t)\, v(t)\, d(t)$
- H-field: $H(t) = \frac{I(t) \cdot N}{l}$
- B-field: $B(t) = \frac{\Phi(t)}{N \cdot A}$ with $\Phi(t_1) = \int_0^{t_1} U_l(t)\mathrm{d}t$
- Core loss: $P_{core} = \frac{A\, l}{T}\int_0^T H(t)\, dB(t)$
- Winding loss: $P_{wind} = P_{tot} - P_{core}$





- Measurements are done without additional winding!!!

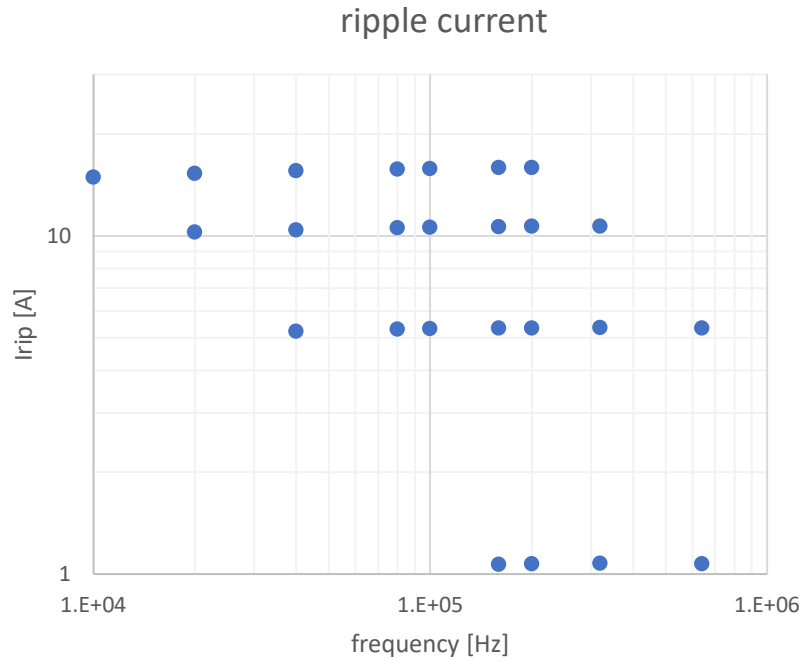
  => no additional winding possible for most commercial parts (eg moulded)

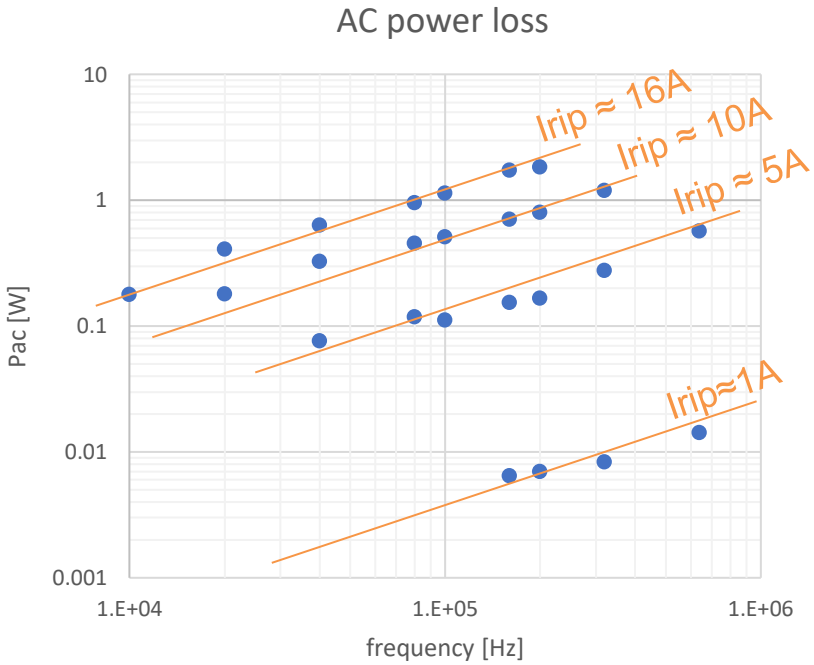
- Verification with additional winding on reference parts shows a deviation of <10% over corner cases

Triangular Flux: AC-power Loss

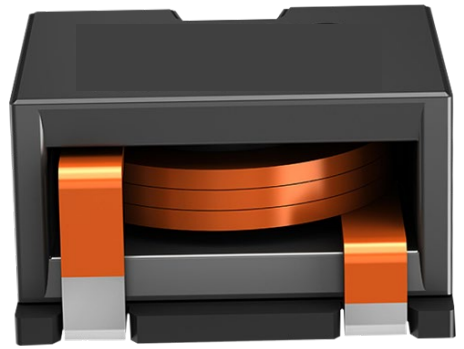
Example Measurements

- Sweep: Current ripple, Frequency @ fixed DC bias = 20A





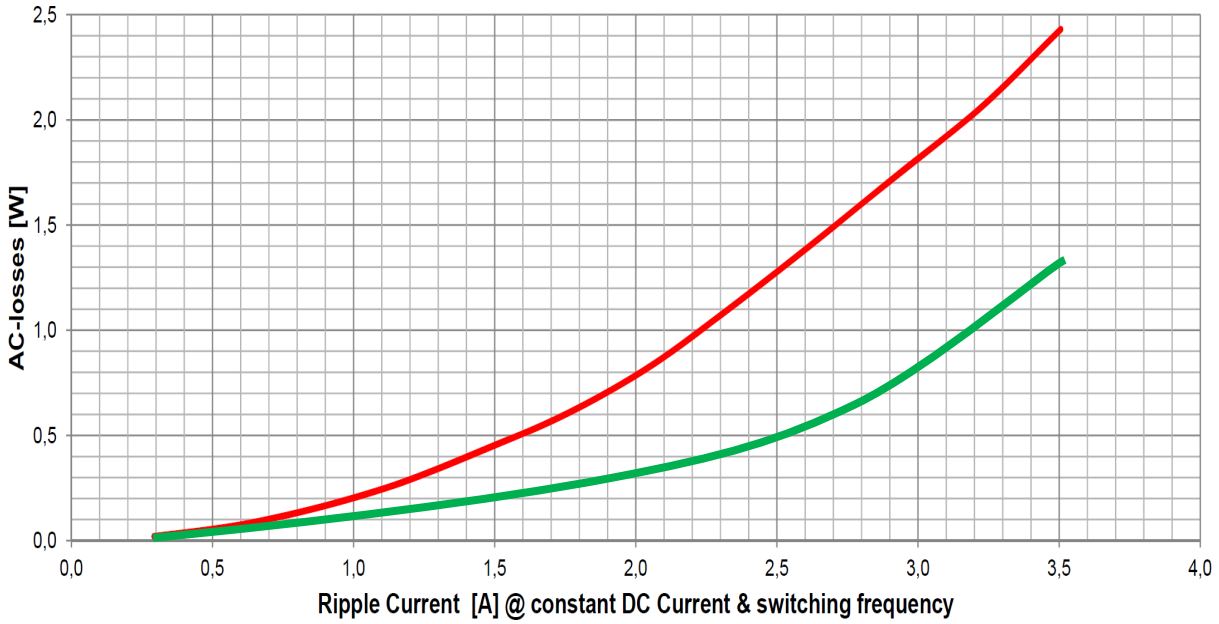
4.7uH, 54A Idc



Triangular Flux: AC-power Loss

Example Measurements

- AC winding loss and core losses @ Current ripple sweep



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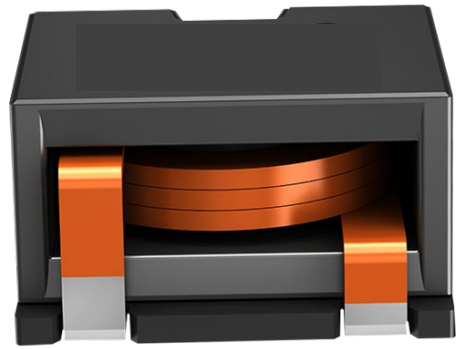
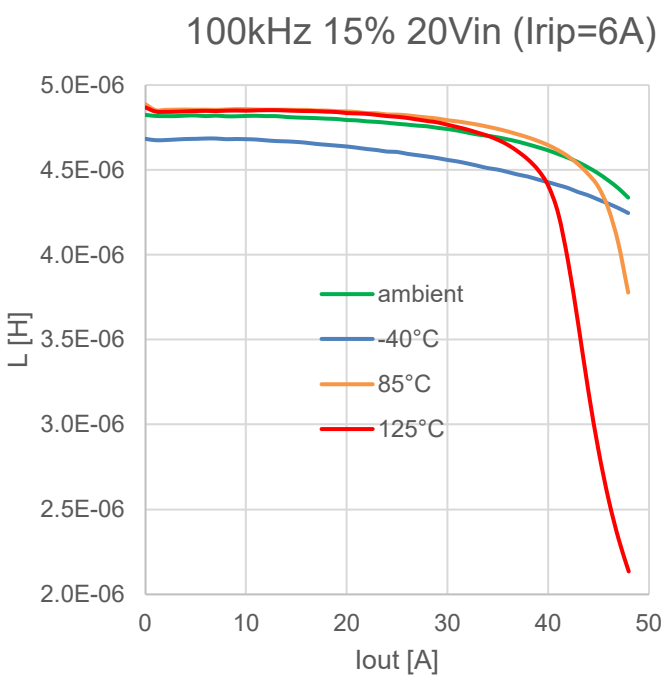
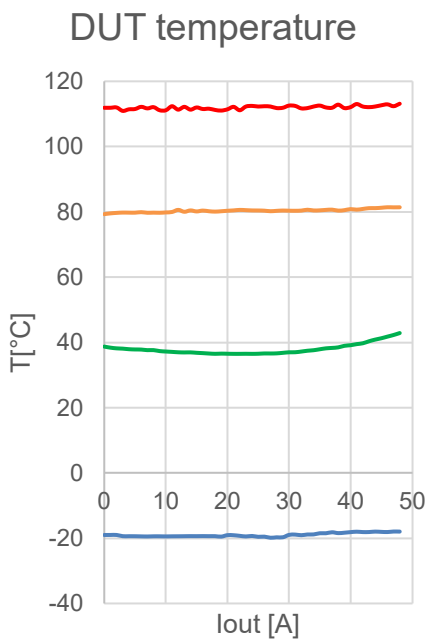


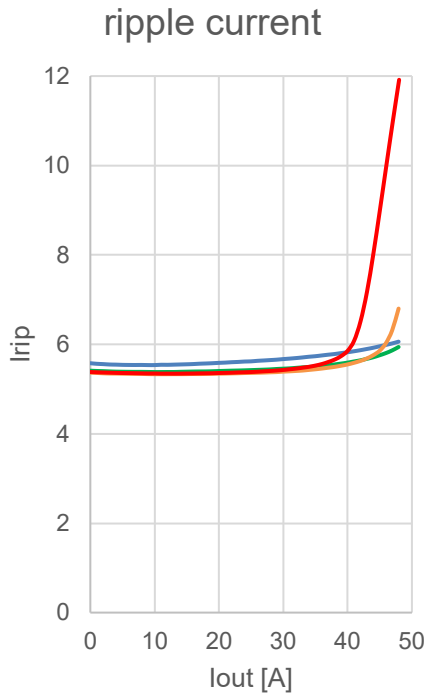
Triangular Flux: AC-power Loss

Example Measurements

- Sweep: DC bias current & Ambient Temperature







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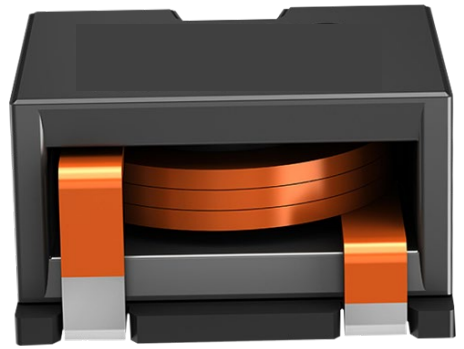
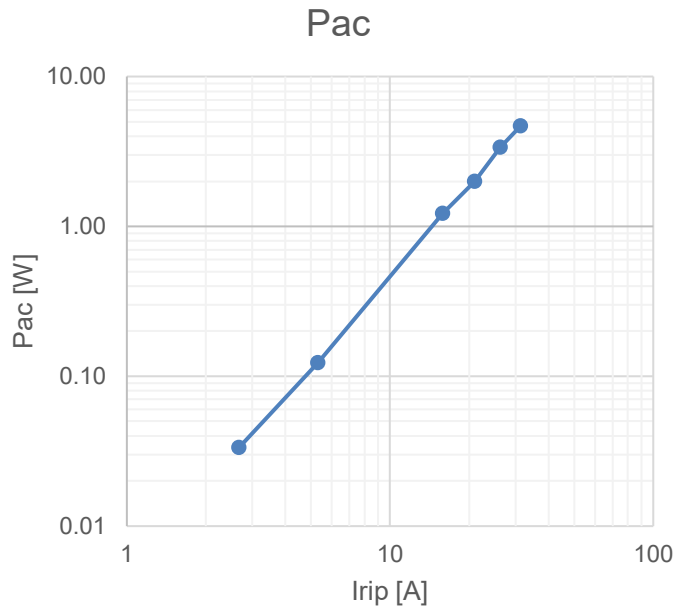
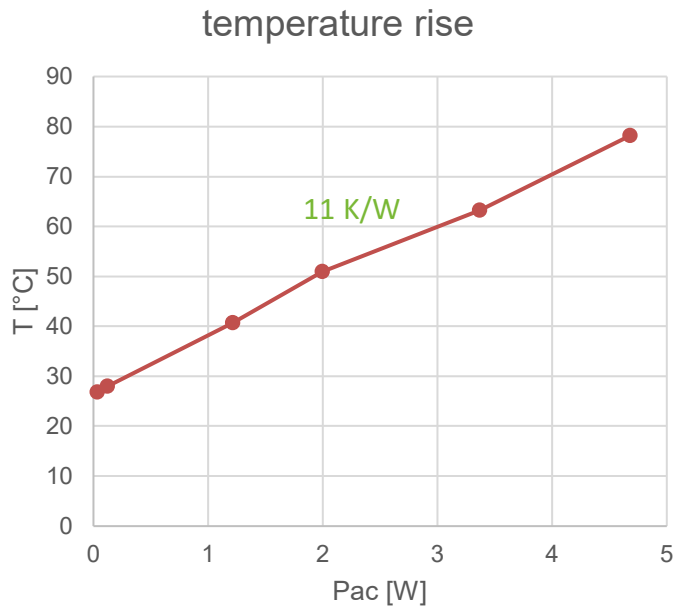


Triangular Flux: AC-power Loss

Example Measurements

- Sweep: Current ripple @ thermal steady-state = 1 hour / point





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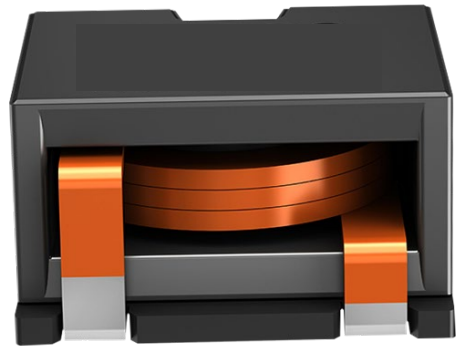
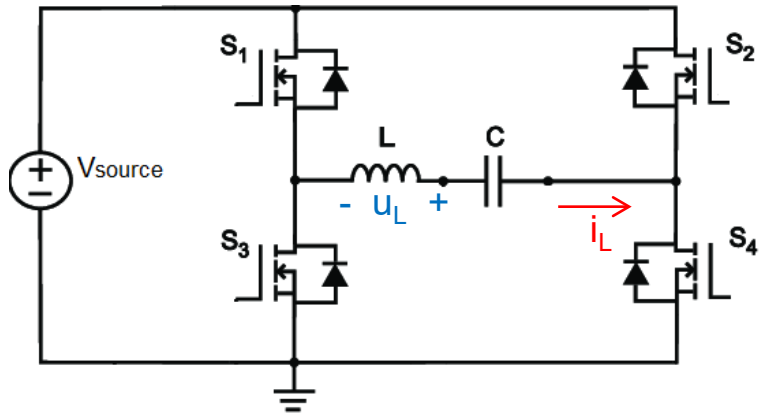
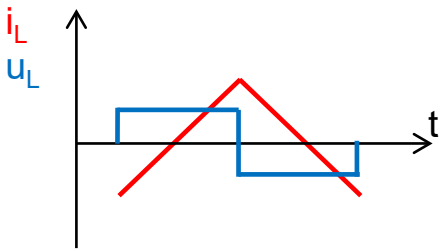


Measuring at High-Voltage

High-Voltage MADMIX

- Principle: Full-Bridge Converter

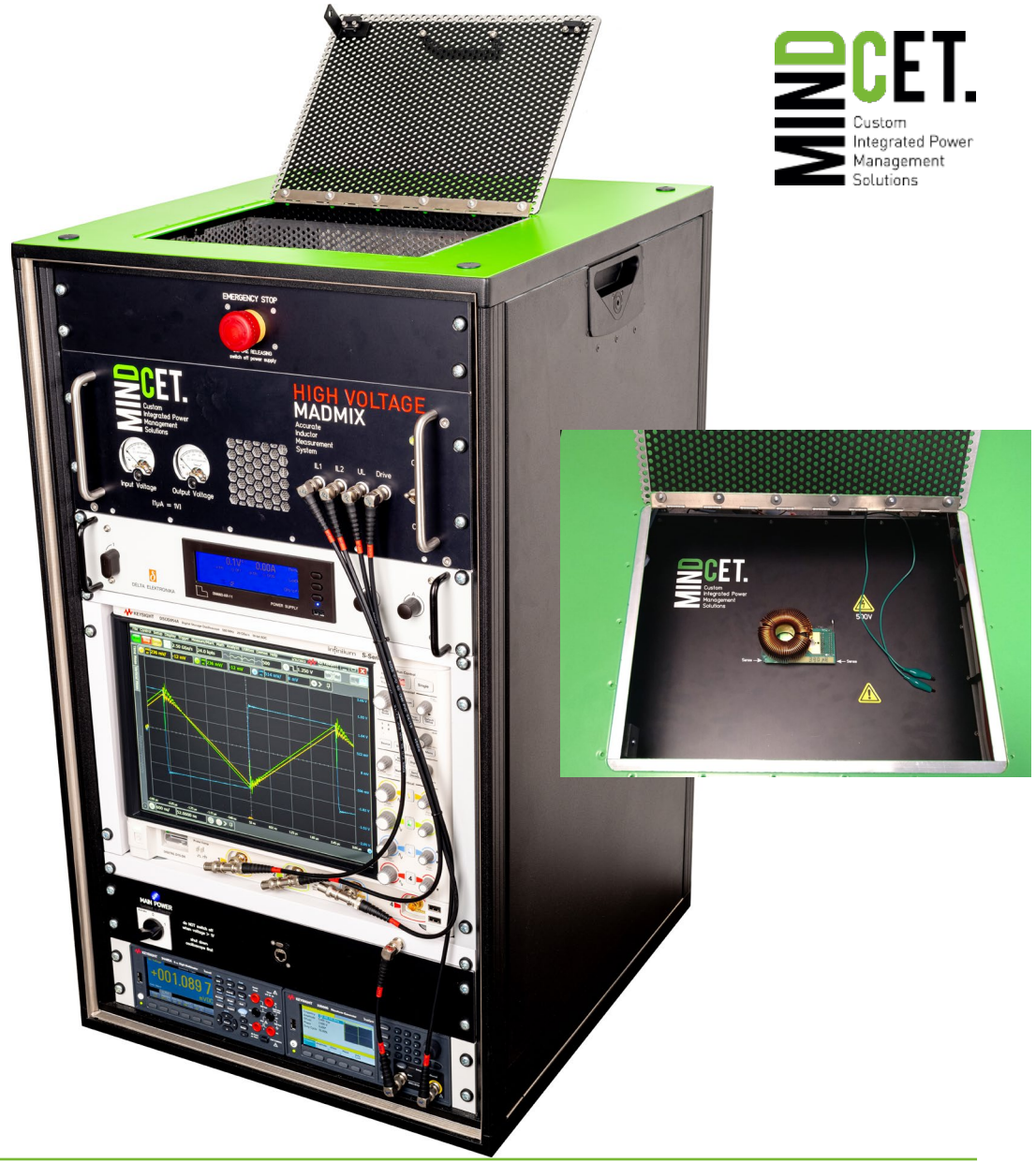




$$Irip = \frac{2.V_{source}.\delta(1-\delta)}{f.L}$$

$$V_C = V_{source}(2\delta - 1)$$

$$\max(V_L) = V_{source} + \mathrm{abs}(VC)$$



Measuring at High-Voltage

High-Voltage MADMIX

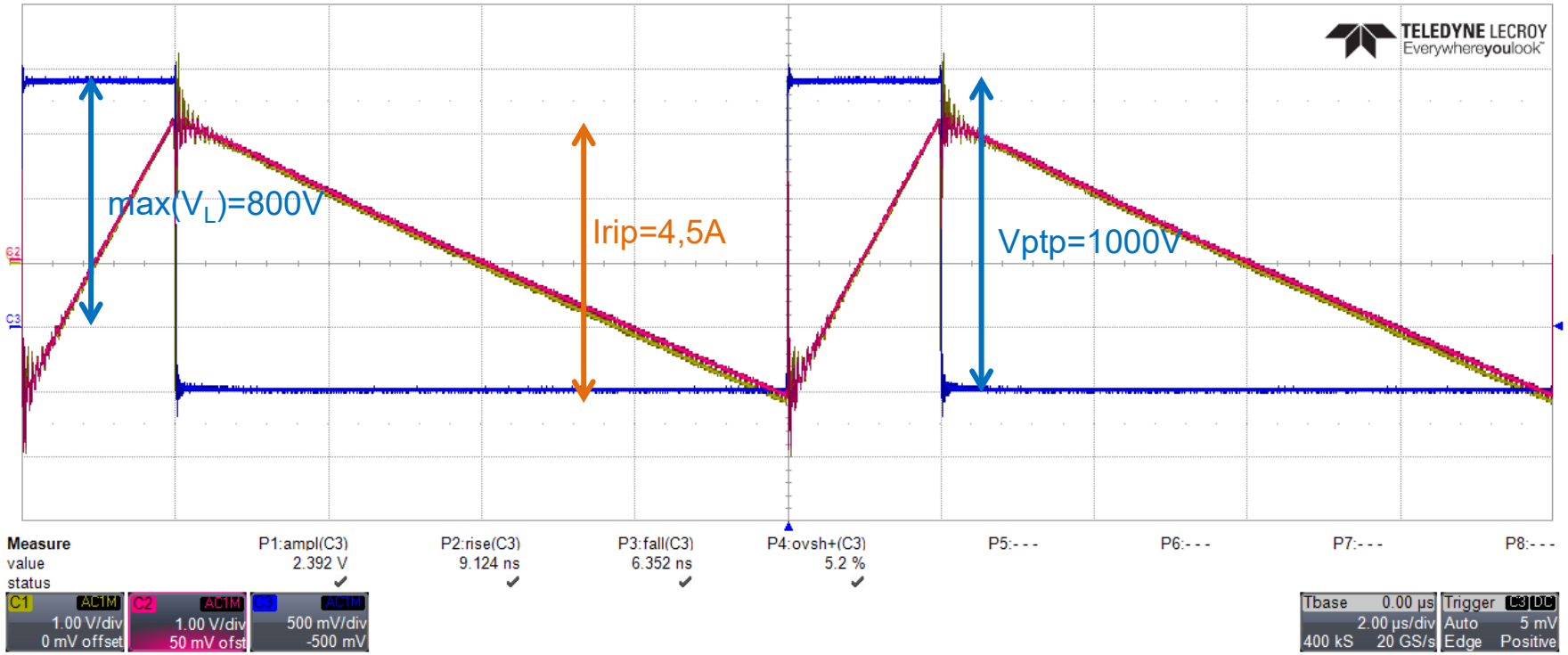
- Specification comparison

Parameter	MADMIX	HIGH-VOLTAGE MADMIX
Input Voltage	0.5-70V	50-500V
Max inductor voltage	66.5V	800V
Max current ripple	120Aptp	60Aptp
Frequency	10kHz-10MHz(15-20)	10kHz-2MHz
Duty-Cycle	5-95%	50-95%
DC bias	0-48A	NA

Measuring at High-Voltage

High-Voltage MADMIX

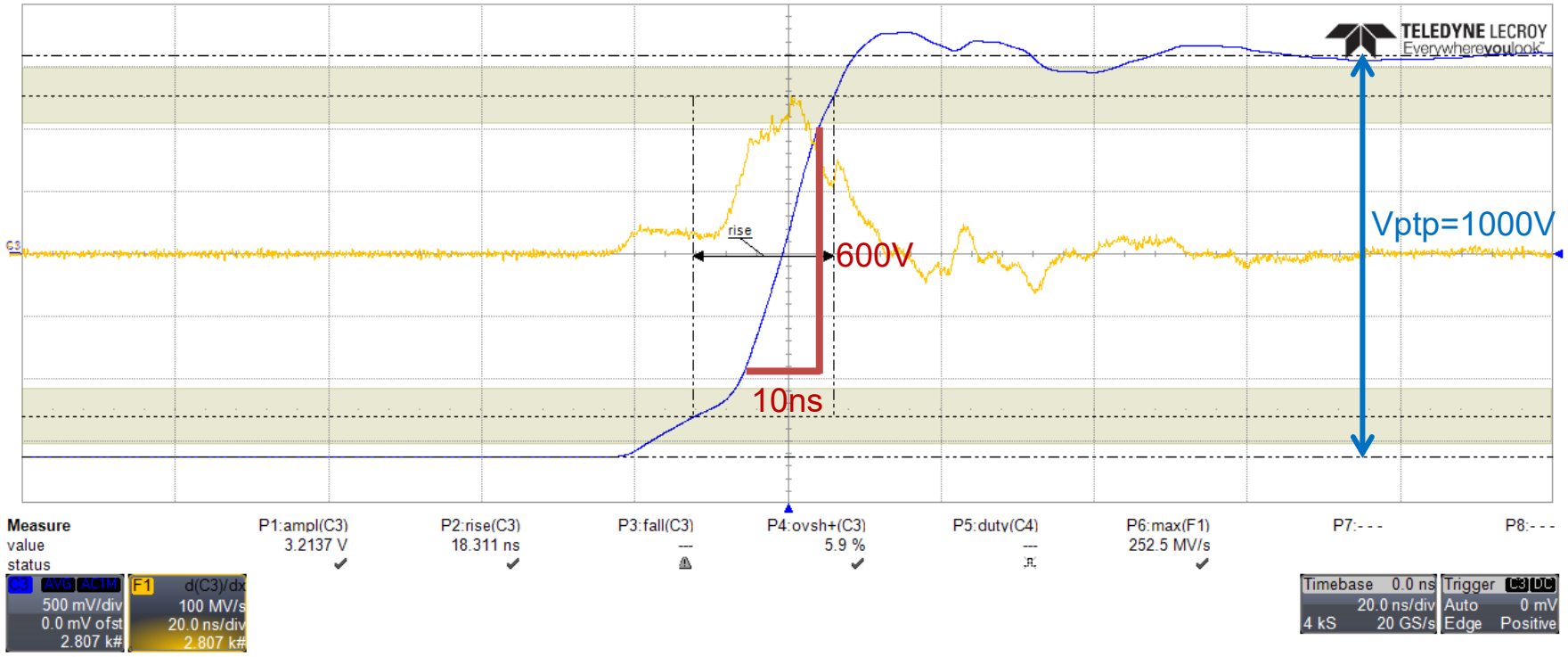
- Real-life waveforms



Measuring at High-Voltage

High-Voltage MADMIX

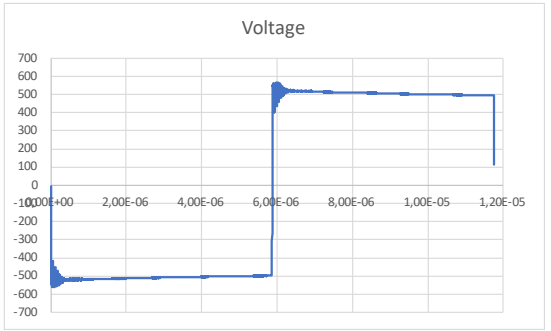
- Real-life waveforms dv/dt = 60V/ns

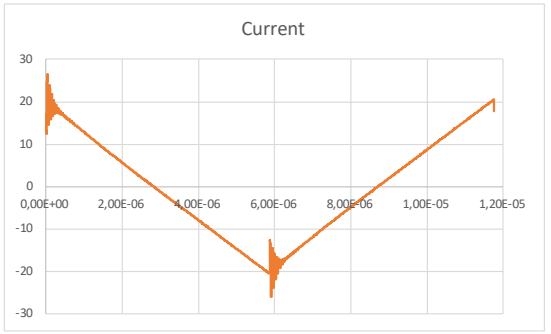


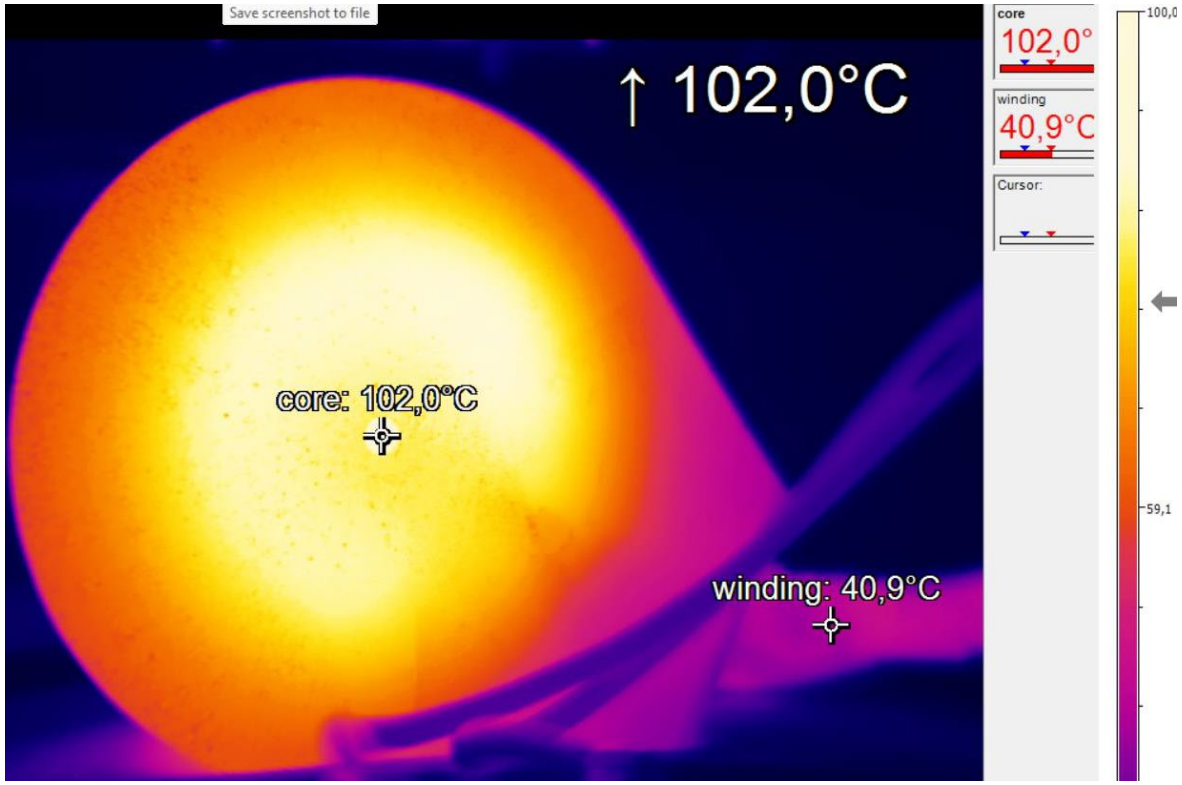
Measuring at High-Voltage

High-Voltage MADMIX

- Allows Pac & Pcore measurements on BIG parts too!!!
- Eg: 75uH, 150A, 3kg inductor
- 1kVptp
- 50% duty
- 85kHz
- 40Aptp
- Pac = 140W



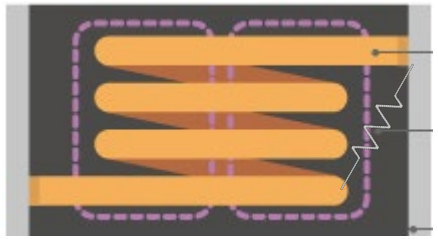


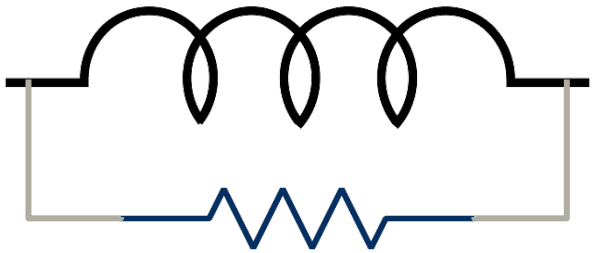


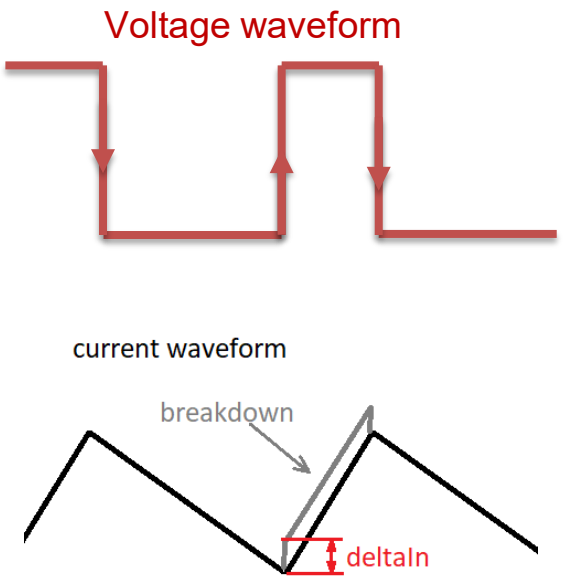
Magnetic Core Voltage Breakdown

Inductor Failure

- Electrically conductive path in the core material
- May occur when a high potential is used to switch the inductor
- Can be modelled as a parallel resistor across the inductance
- Causes a “jump” in the current waveforms

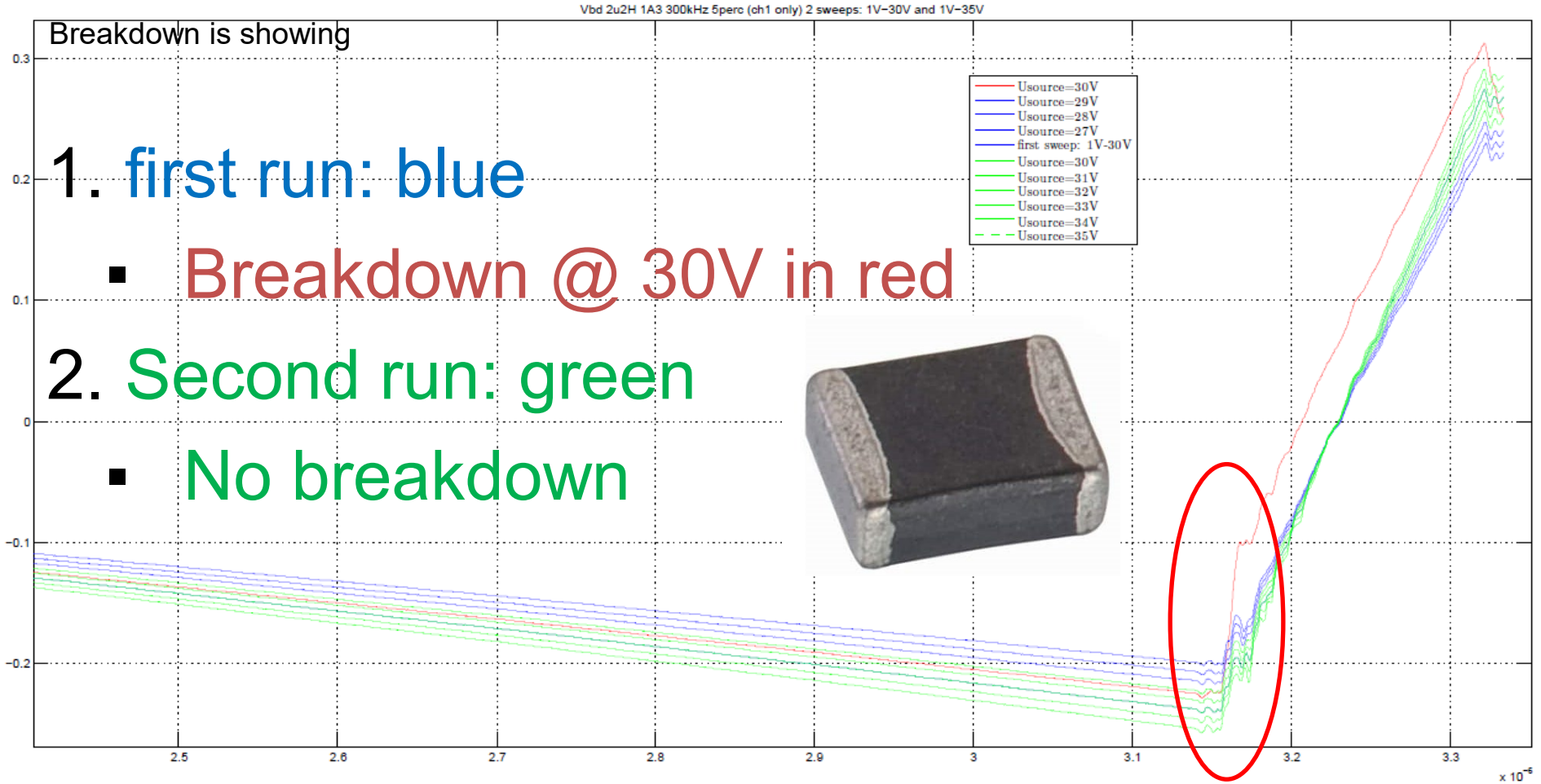






Magnetic Core Voltage Breakdown

Inductor Failure

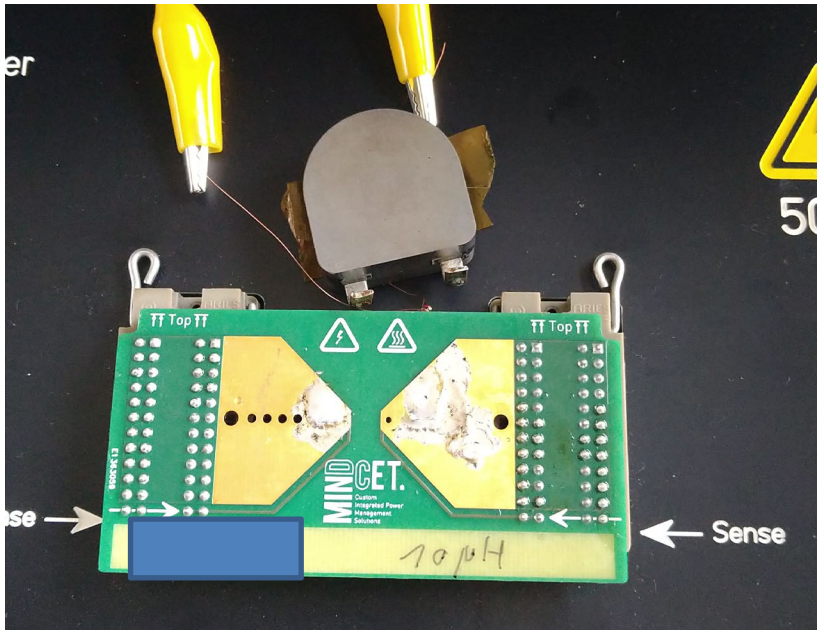


1. first run: blue
   - Breakdown @ 30V in red
2. Second run: green
   - No breakdown

Magnetic Core Voltage Breakdown

Inductor Failure

- It remains a tricky measurement
- Other failure mechanisms may occur sooner
- Such as…thermal breakdown, solder joints…
- BBQing parts may be a side-effect



Transformers

Coupled inductors

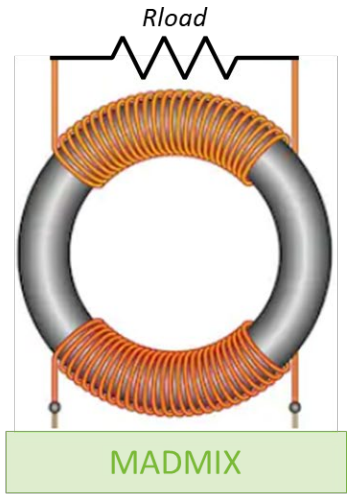
- Open-Short method, 2-steps
- Allows to measure the coupling factor (leakage inductance)
- All other parameters can also be measured (AC-losses, core loss, voltage breakdown of core…)

OPEN secondary

$$L = L_{prim}$$

SHORTED secondary

$$L = L_{prim}(1 - k^2)$$



LOADED secondary

$$L = L_{prim}\left(1 - \frac{k^2}{1 + \left(\frac{R_{load}}{\omega L_{sec}}\right)^2}\right)$$

$$R_{refl} = \frac{k^2}{n^2}\frac{R_{load}}{1 + \left(\frac{R_{load}}{\omega L_{sec}}\right)^2}$$

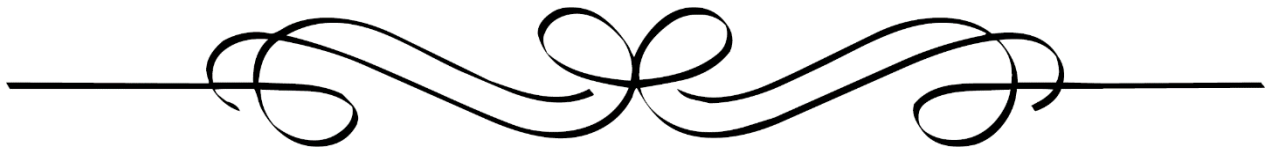
Outlook

What the future will bring

- Become the standard for measuring SMPS capacitors -> MADMIX (equivalent for inductors) has preceeded this already
- Comparing different types and brands in an objective way to make a fair comparison$
- Stressing inductors/transformers as in the application will allow improved reliability analysis, avoiding over- or under-design
- Keep ahead of State-of-the-Art SMPS by increasing frequency range to 15-20MHz of the standard MADMIX (new power amp is validated as we speak)
- Add software functionality to measure (Brushless) DC motor coils and their losses
- In the end bring new insights in one of the oldest components in electronics
- …Feel free to share your ideas!

Conclusions

- MADMIX is unique and additional way to measure SMPS inductors with real-life stimuli: TRIANGULAR FLUX
- All crucial parameters can be measured, including Inductance, core loss, winding loss, DCR, temperature increase, BH-loop, saturation…
- HIGH-VOLTAGE MADMIX allows measuring bigger parts, higher inductances and core breakdown effects.



Biography

Dr. ir. Ing. Mike Wens received the Master of Engineering degree in electronic design techniques from the Karel de Grote Hogeschool, Antwerp, Belgium, in 2004. In 2006 he received the Master of Science degree in microelectronics from the Katholieke Universiteit Leuven, Leuven, Belgium. From 2006 on, he worked as a research assistant at the ESAT-MICAS (MICroelectronics And Sensors) laboratories (K.U.Leuven) towards his PhD degree entitled *"Monolithic Inductive CMOS DC-DC Converters"*, which he achieved in 2010. In 2011 he co-founded MinDCet NV, a mixed-signal Power Management IC design center, together with Dr. Ing. Jef Thoné. His extensive knowledge in the field of switched mode power supplies, both discrete and (fully-)integrated dates back to 2002. Together with Dr. Ing. Jef Thoné he is the co-inventor of the patented MADMIX and MADCAP equipment to measure the core loss of SMPS inductors under large-signal triangular flux excitation and the losses of SMPS capacitors under real-life operating conditions. His other interests are analog & high-voltage mixed-signal IC design, high-voltage applications, renewable energy, discrete design, LED-lighting, High-End tube amplifiers and analog & digital photography.

What can we do for you?

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