ACCURACY AND COMPENSATION ISSUES FOR AC POWER LOSS MEASUREMENTS

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Motivation

- Loss measurement for ferrites using toroidal cores (according to standard) → material charcterization
- Reproducibility of the measurement was determined
- Measurement accuracy is examined in this presentation
  - For sinusoidal waveforms
  - For high frequencies
- Good data accuracy is essential
  - Comparability between materials and manufacturers
  - Good predictions in simulation
- **Challenge: Compensation of the time delay in the signal paths → high loss measurement accuracy**

Test bench

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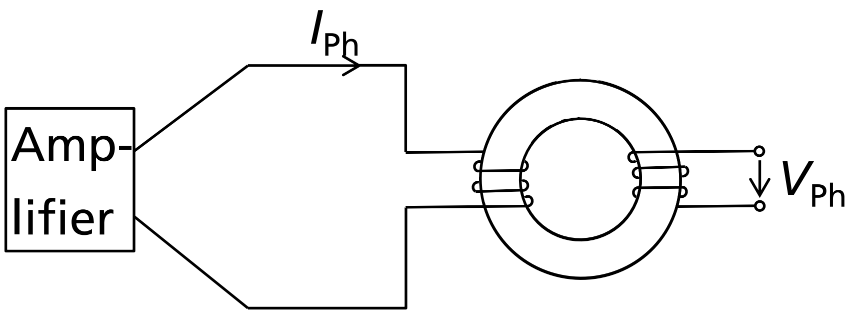

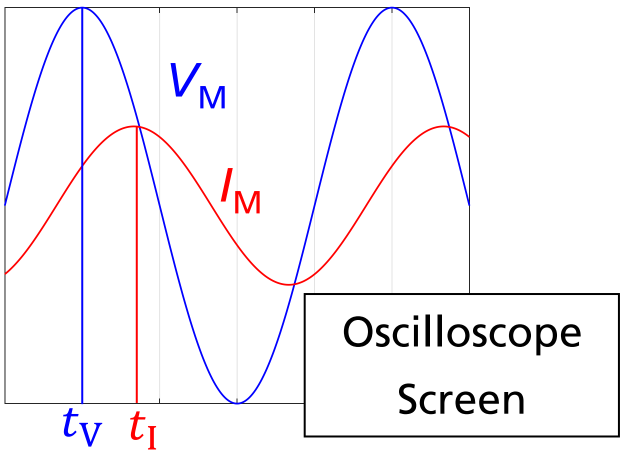

Device Under Test (Toroidal Core):

→ Physical phase between V_{Ph} and I_{Ph} leads to time delay: Δt_{Ph} → $\Delta\phi_{\mathrm{Ph}} = 2 \cdot \pi \cdot f \cdot \Delta t_{\mathrm{Ph}}$

Physical: $t_{\mathrm{V}} - t_{\mathrm{I}} = \Delta t_{\mathrm{Ph}}$

Screen: $t_{\mathrm{V}} - t_{\mathrm{I}} = \Delta t_{\mathrm{Ph}} + \Delta t$

- Shift Δt between voltage and current due to time delay in the signal paths → turns as: $\Delta\phi = 2 \cdot \pi \cdot f \cdot \Delta t$ → high sensitivity of loss measurement
- Measured phase of the impedance: $\phi_{err} = \Delta\phi_{\mathrm{Ph}} + \Delta\phi$

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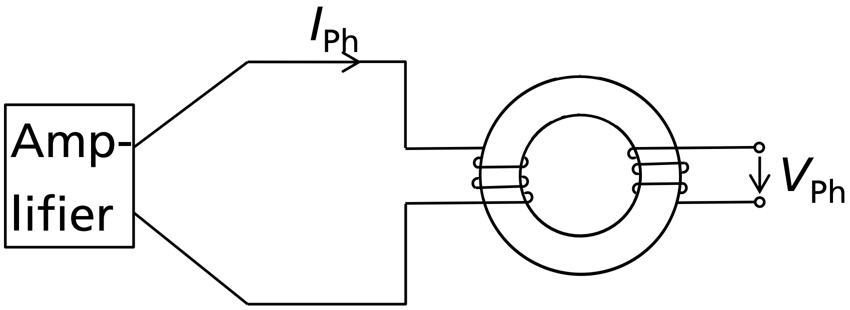

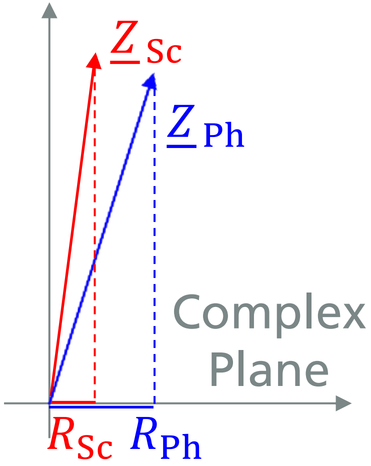

Device Under Test (Toroidal Core):

→ Physical phase between V_{Ph} and I_{Ph} leads to time delay: $\Delta t_{Ph} \rightarrow \Delta\phi_{Ph} = 2 \cdot \pi \cdot f \cdot \Delta t_{Ph}$

Physical: $R_{Ph} = |Z| \cdot \cos(\Delta\phi_{Ph})$

Screen: $R_{Sc} = |Z| \cdot \cos(\Delta\phi_{Ph} + \Delta\phi)$

- Shift Δt between voltage and current due to time delay in the signal paths → turns as: $\Delta\phi = 2 \cdot \pi \cdot f \cdot \Delta t$ → high sensitivity of loss measurement
- Measured phase of the impedance: $\phi_{err} = \Delta\phi_{Ph} + \Delta\phi$

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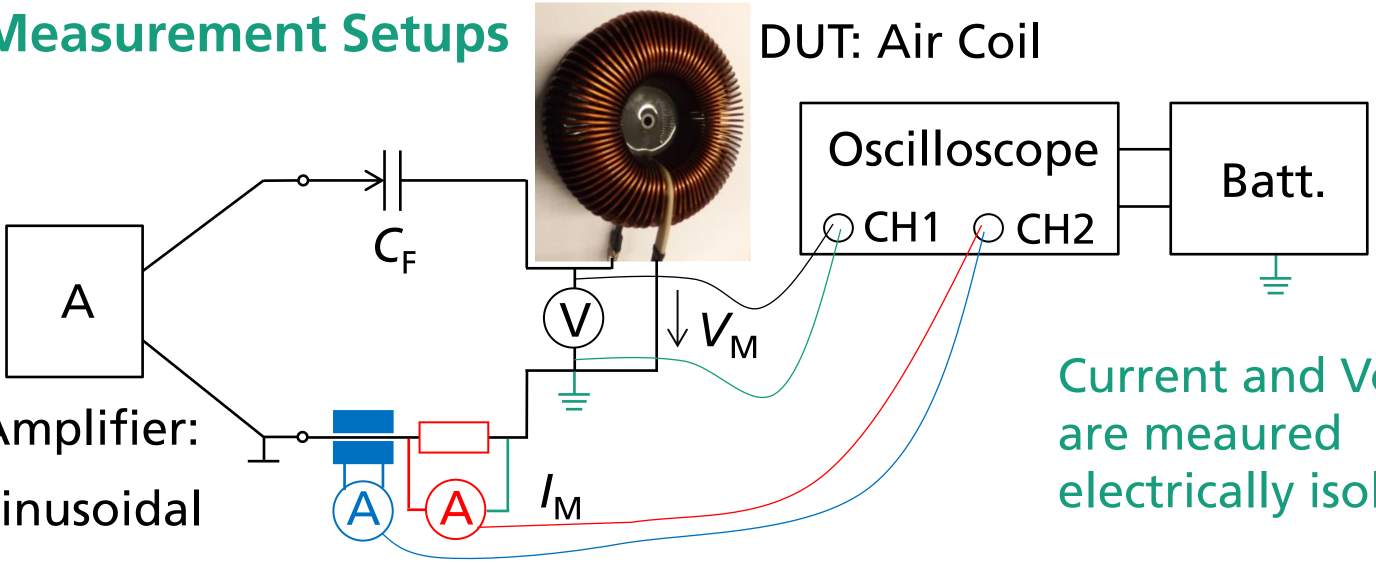
Measurement Setups



Amplifier:

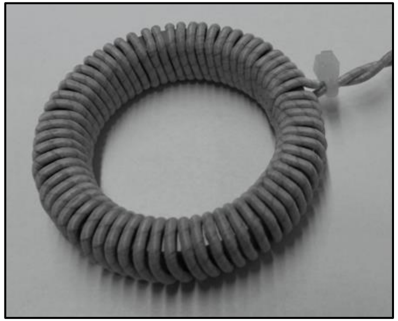
Sinusoidal

Current and Voltage are meaured electrically isolated ⏚

- Setup 1: Current sensing → active current probe
  Voltage sensing → active voltage probe
- Setup 2: Current sensing → pearson current monitor
  Voltage sensing → passive voltage probe [1-2]
- Setup 3: Current sensing → Shunt [3]; Voltage sensing → passive voltage probe

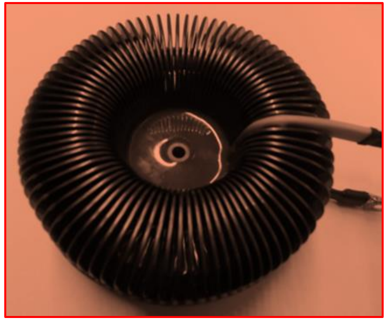
Reference Air Coils

Air Coil 1	
Inductance	3 [μH]
$\Delta\phi_{\mathrm{Ph}}$	> 87.5 °
Current	1 App
Frequency range	100 kHz-1MHz



Air Coil 2	
Inductance	3 [μH]
$\Delta\phi_{\mathrm{Ph}}$	> 87 °
Current	1 App
Frequency range	100 kHz-1MHz

Air Coil 3	
Inductance	30 [μH]
$\Delta\phi_{\mathrm{Ph}}$	> 88.5 °
Current	100 mApp
Frequency range	100 kHz-1MHz



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Measurement Setups and Reference Coils

Phase Measurements using Reference Coils

Loss Measurement Accuracy

Measurement Accuracy: Triangular Currents

Summary and Outlook

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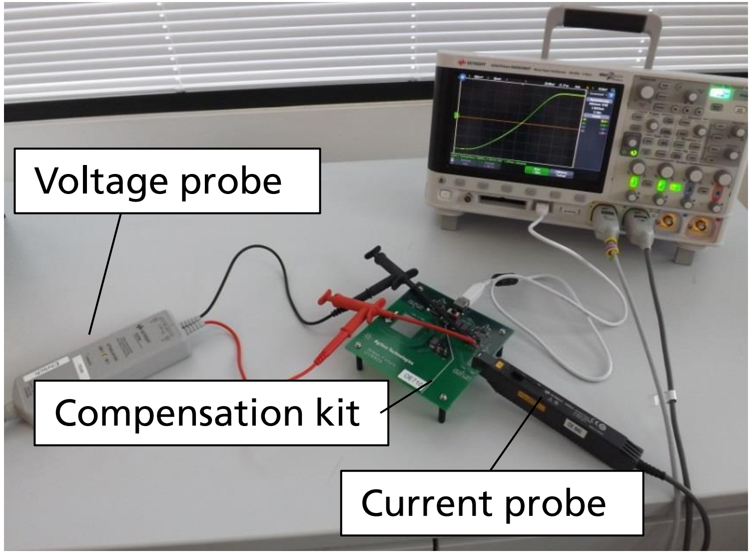
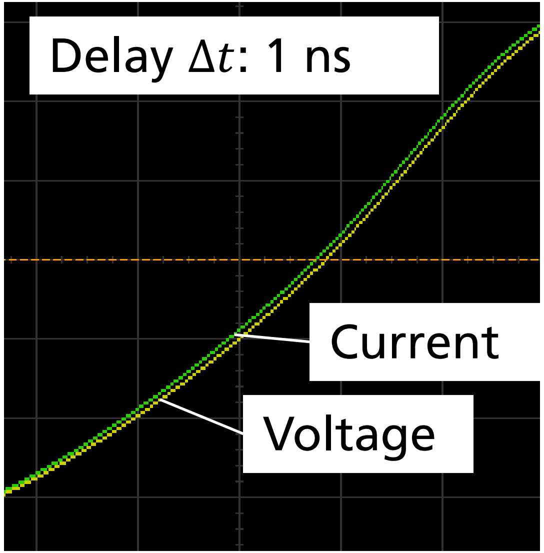
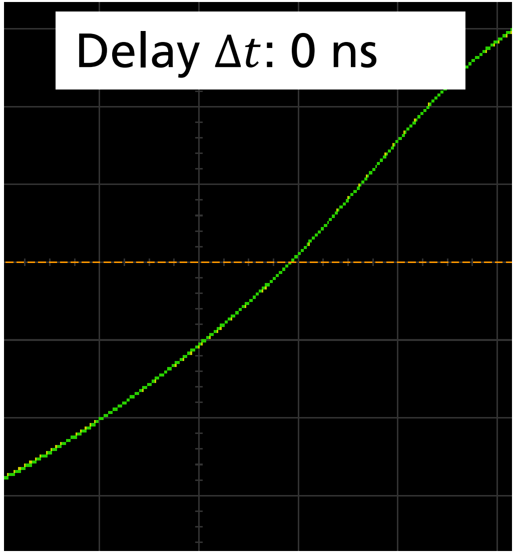
Setup 1: Active Voltage Probe and Active Current Probe







- Determining the time delay Δt by using a compensation kit
- We assume the delay between current and voltage to be 0 ns → best match of voltage and current signals

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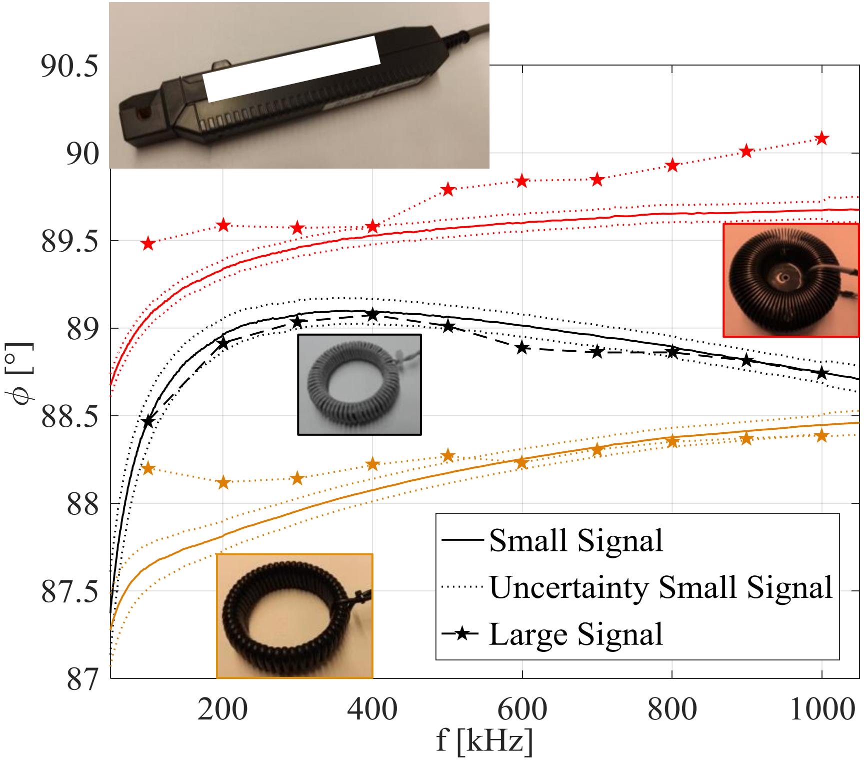
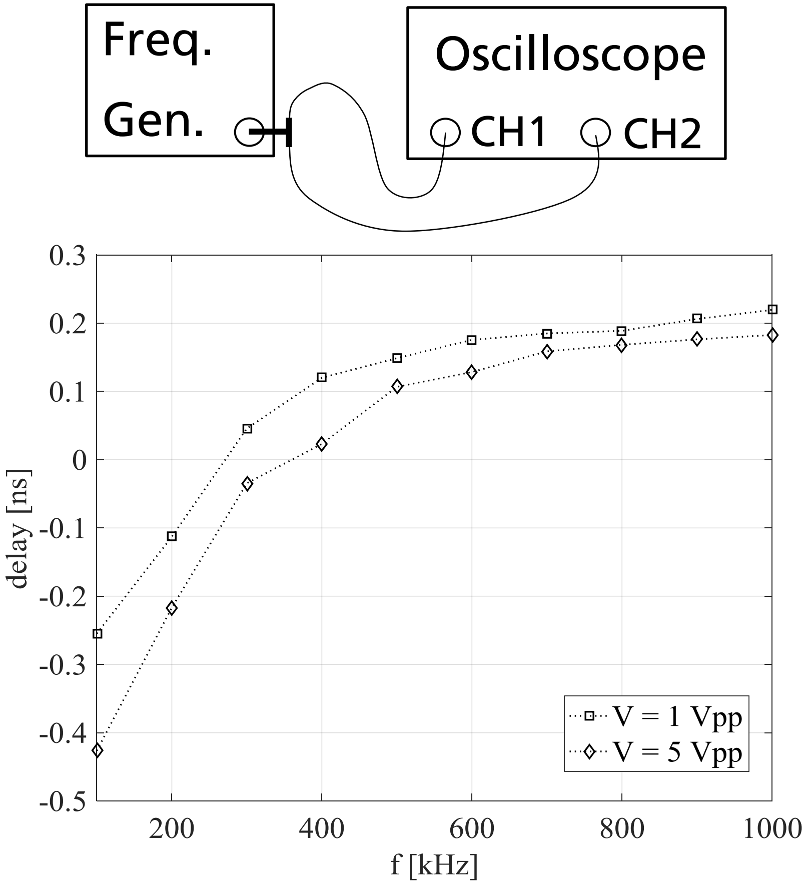
Setup 1: Active Voltage Probe and Active Current Probe

- Small signal measurement with the impedance analyzer as a reference
- Small and large signal measurement for the black coil match very well
- Measurements deviate strongly for the other coils especially at small frequencies
- Although the signal delay was compensated using a compensation kit, there are still large deviations within the measurement.



Time Delay of Voltage Probes and Oscilloscope

- Measurement of a sinusoidal signal using two 10:1 voltage probes and a oscilloscope
- Measurement includes the time delay between channel 1 and 2 as well as between the 10:1 voltage probes
- Time delay is much smaller than 1 ns within the examined frequency range
- The dependency on the voltage magnitude is prooved to be small



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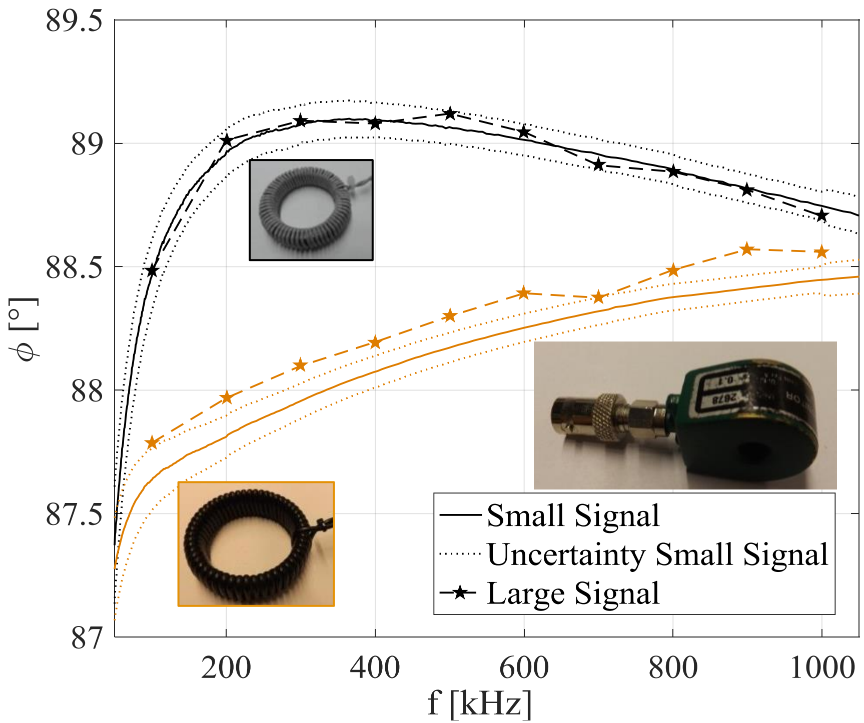
Setup 2: Passive Voltage Probes and Pearson Current Monitor

- Time delay of voltage probes and oscilloscope is compensated for high frequencies
- Time delay of the current monitor is fitted that curve characteristics match; delay is the same for both coils
- Small and large signal measurement for the black coil match very well
- Measured curve characteristics for the yellow coil are similar



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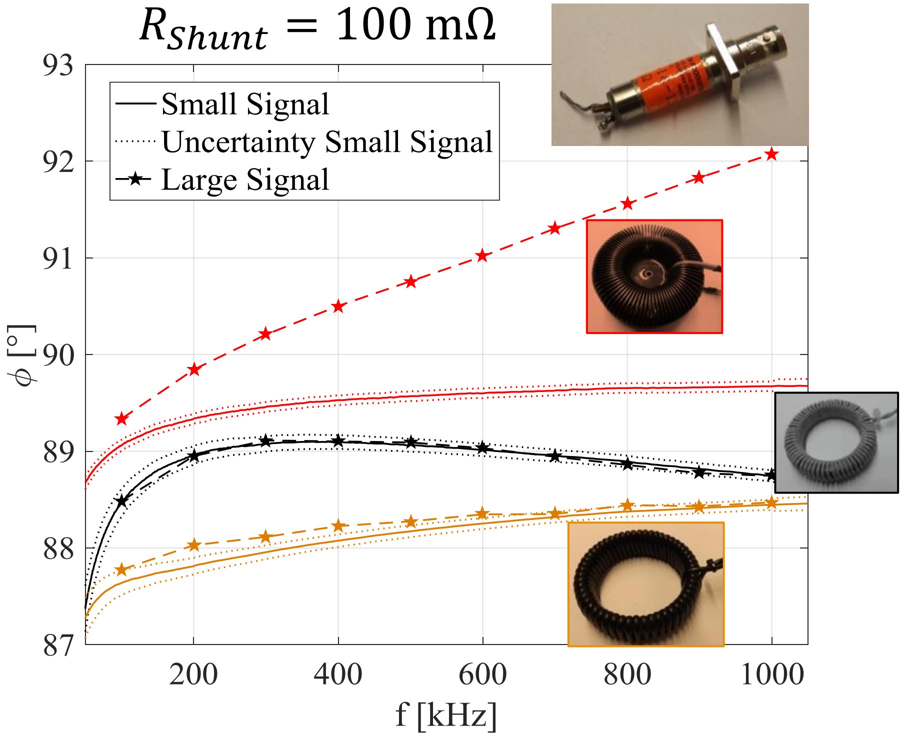
Setup 3: Passive Voltage Probes and Shunt 1

- Time delay of voltage probes and oscilloscope is compensated for high frequencies
- Time delay due to the Shunt inductance (≈120 pH) is compensated
- Small and large signal measurement for the black and yellow coil match very well
- Measurements for the red coil deviate strongly → as expected: measuring voltage in the range of the input white noise of the scope



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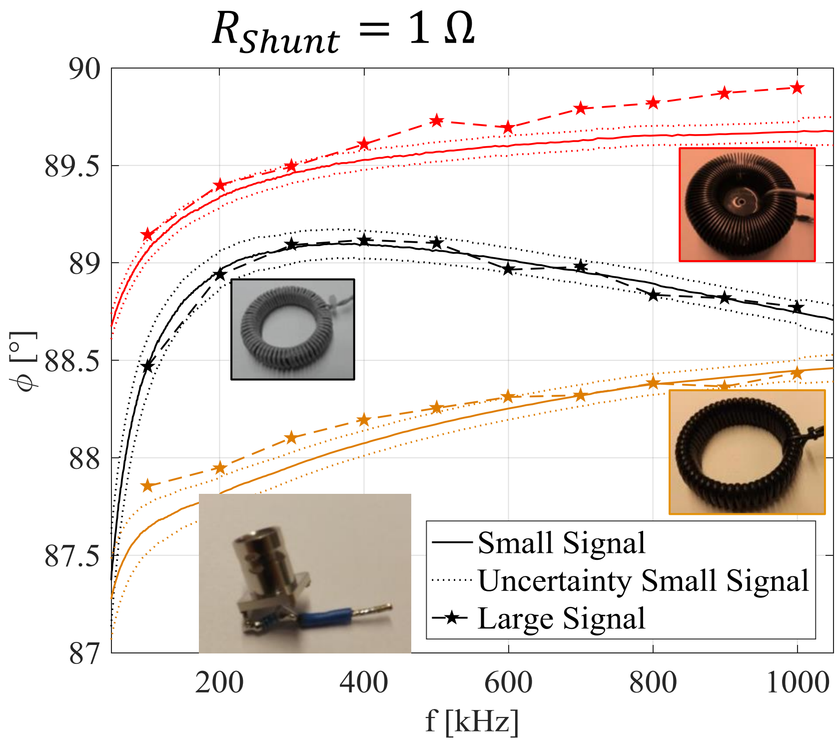
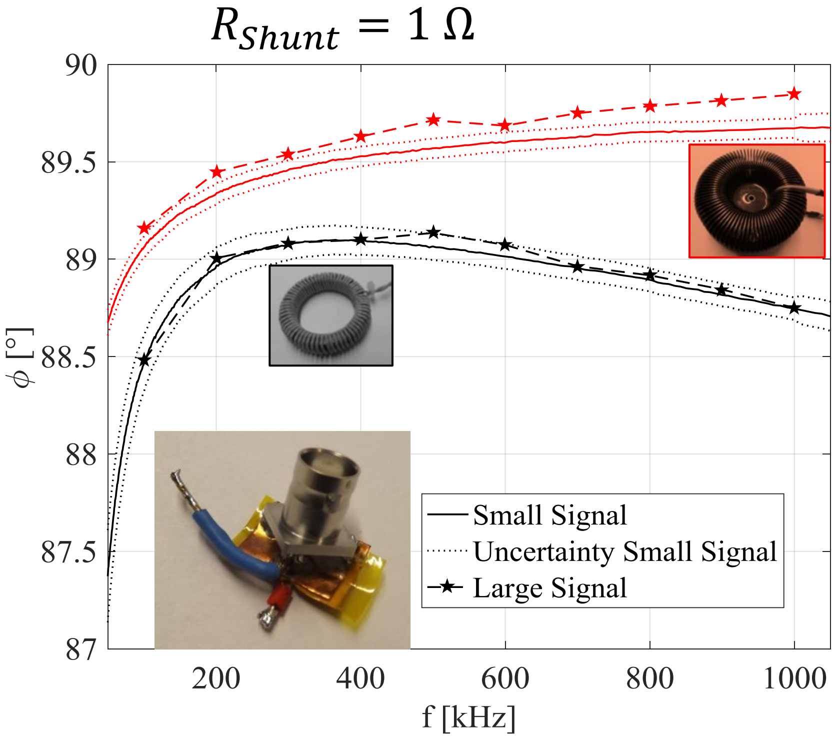
Setup 3: Passive Voltage Probes and Shunt 2

- To improve sensitivity a wired shunt was built up
- Shunt inductance, which causes a delay in the current sensing, can't be measured exactly
- Choosing the same shunt inductance (≈ 2.4 nH) for all measurements → time delay is compensated
- Even for the red coil measurement accuracy is improved



Setup 3: Passive Voltage Probes and Shunt 3

- Self-built low-cost shunt for ultra low inductance [4] Gerstner
- Simulations and measurements suggest that shunt inductance is <300 pH
- Small and large signal measurement for the black coil match very well
- Using this shunt, the highest measurement accuracy for the red coil was achieved



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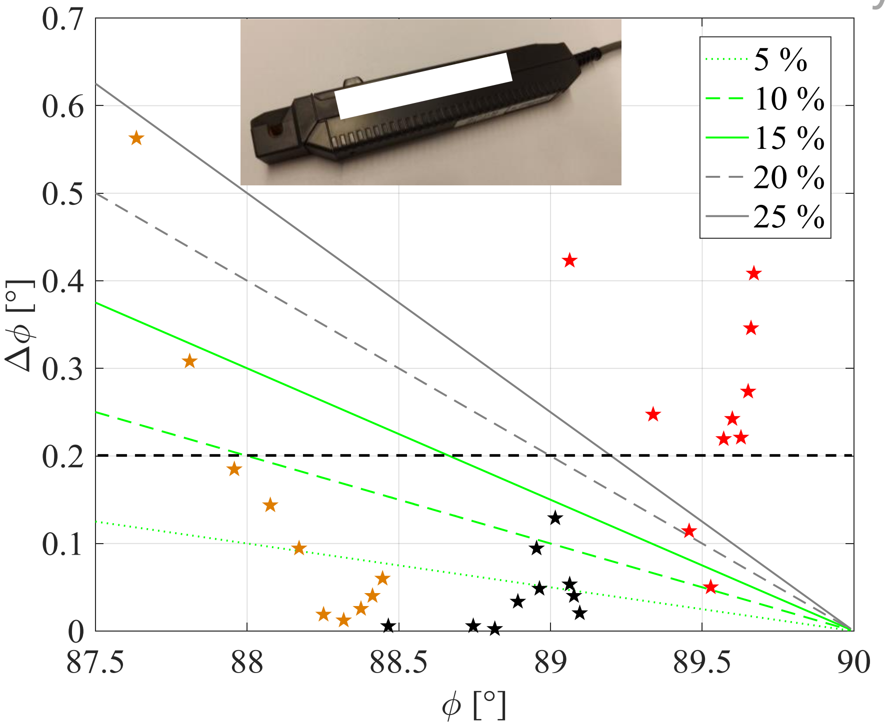
Loss Measurement Accuracy: **Setup 1**

- Small signal measurement of phase: ϕ_{sm}
- Phase deviation between small signal and large signal measurement: $\Delta\phi$
- Using setup 1, the uncertainty in loss measurement for the yellow coil is up to 25 %

uncertainty

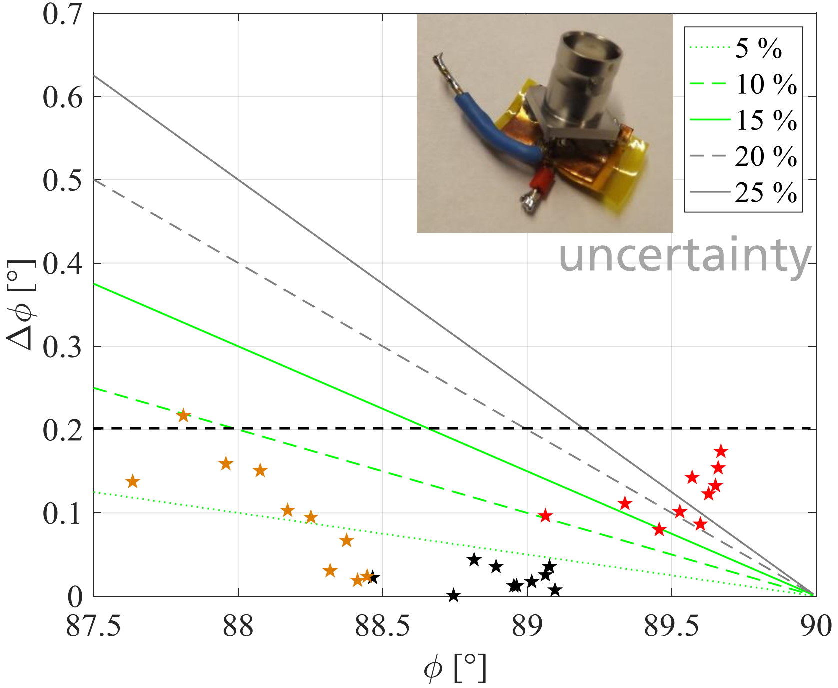


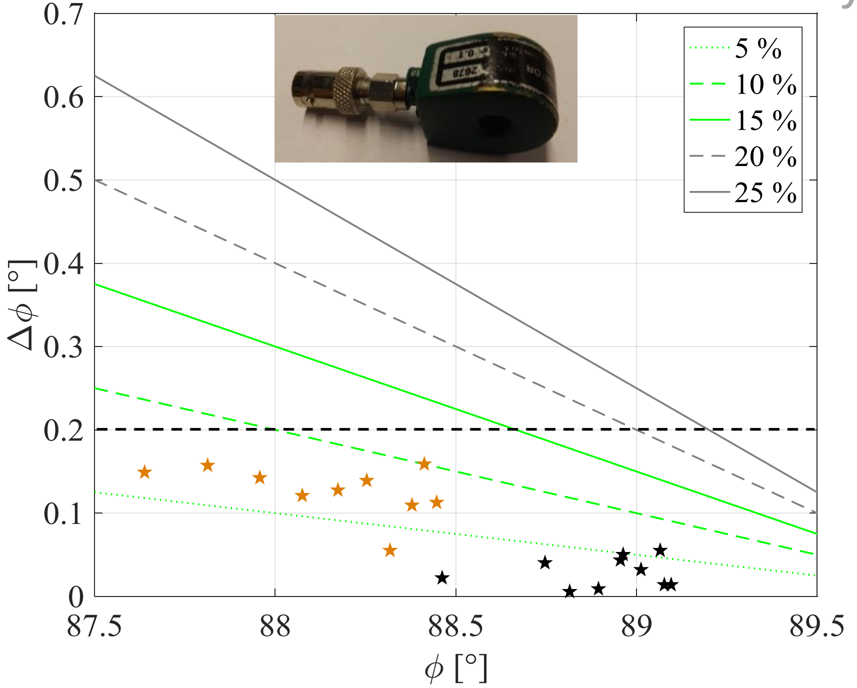
<u>Uncertainty is defined as:</u>

$$\left|\frac{\cos(\phi_{sm} \mp \Delta\phi) - \cos(\phi_{sm})}{\cos(\phi_{sm})}\right| \cdot 100\ \%$$

Loss Measurement Accuracy: Setup 2 and 3

uncertainty

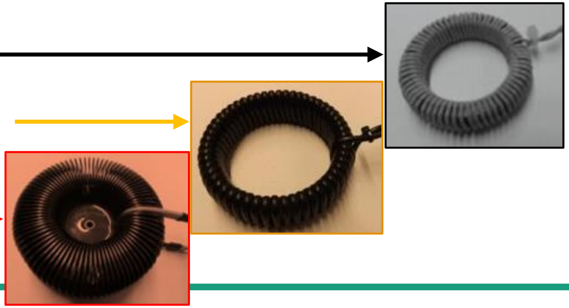




→ Uncertainty of loss measurement: within 5 % for the black coil and 10 % for the yellow coil

Loss Measurement Accuracy: **Conclusion**

- Setup 1: Active Voltage Probe and Active Current Probe
  - ✗ Uncertainty for the black coil within 15 %
  - ✗ Uncertainty for the yellow coil within 25 %
- Setup 2: Passive Voltage Probes and Pearson Current Monitor
  - Uncertainty for the black coil within 5 %
  - Uncertainty for the yellow coil within 10 %
- Setup 3: Passive Voltage Probes and Shunt
  - ✓ Uncertainty for the black coil within 5 %
  - ✓ Uncertainty for the yellow coil within 10 %
  - ✓ Highest accuracy for the red coil



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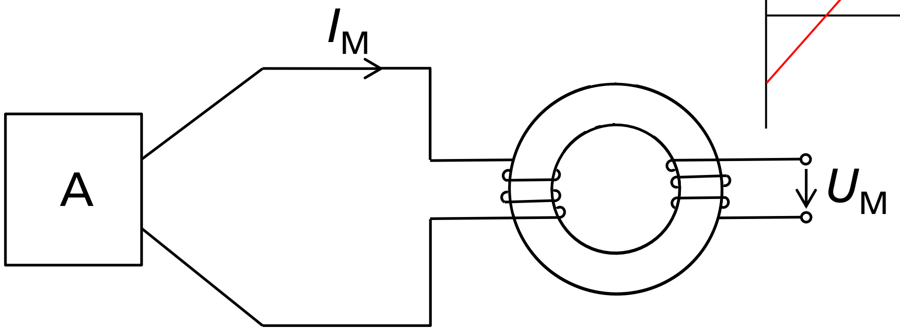
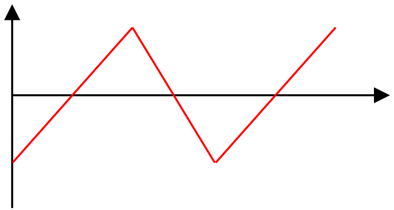
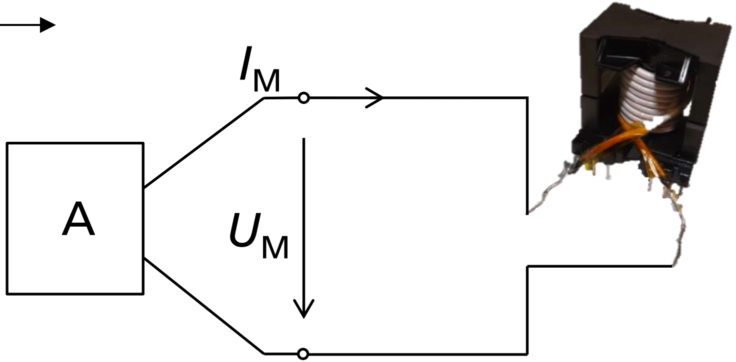
Measurement Accuracy: Triangular Currents

Core losses





Coil losses



- Measurement of core or coil losses with triangular, trapezoidal currents
- Time delay in the signal paths must be constant in a wide frequency range
  - Using a shunt → there's no delay in the current sensing
  - Using a current monitor → Examination of time delay depending on excitation

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Summary and Outlook

- Three different measurement setups were tested refering loss measurement accuracy
- Using a pearson current monitor or a shunt, measurement uncertainty for the examined coils is similar
- To cover the whole current range, different shunts and current monitors are necessary
- Excitation with triangular currents: time delay in the signal paths must be constant in a wide frequency range
- Verification of the measurement accuracy with triangular currents

Any Questions

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References

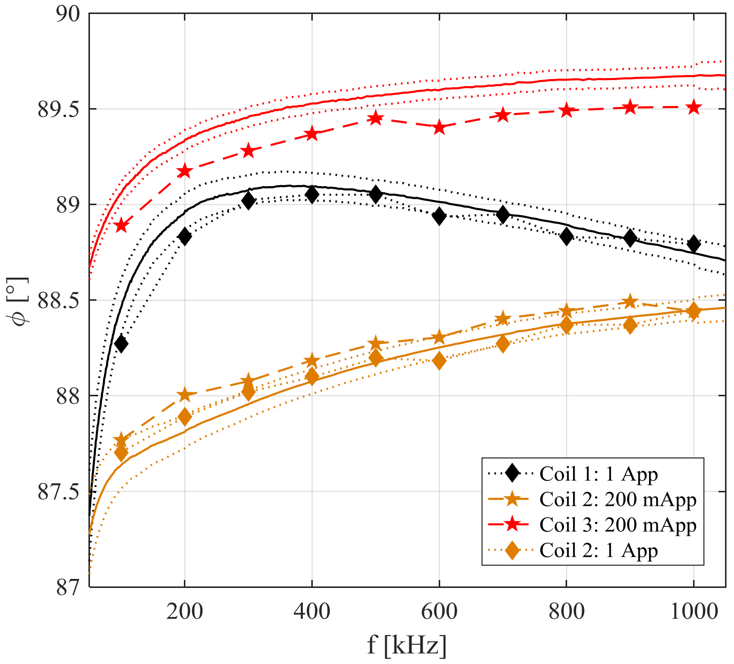
[1] J. Niedra, "Performance of the NASA Digitizing Core-Loss Instrumentation,"

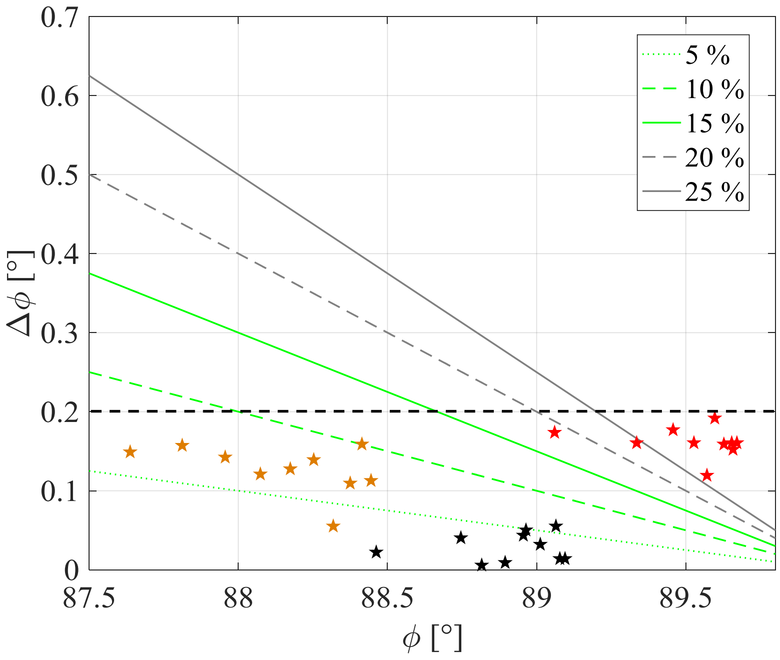
[2] J. N. Lester and B. M. Alexandrovich, "Compensating power measurement phase delay error - Industry Applications Conference, 1999. Thirty-Fourth IAS Annual Meeting. Conference Record of the," IEEE 1999.

[3] J. A. Ferreira, W. A. Cronje, and W. A. Relihan, *Integration of high frequency current shunts in power electronic circuits*, IEEE 1992.

[4] Holger Gerstner, Thomas Heckel, Achim Endruschat, Andreas Rosskopf, Bernd Eckardt, Martin Maerz, "SiC Power Module Loss Reduction by PWM Gate Drive Patterns and Impedance-Optimized Gate Drive Voltages,"

Setup 2: Passive Voltage Probes and Pearson Current Monitor





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