A New Series of High Frequency Core Loss Measurement Methods

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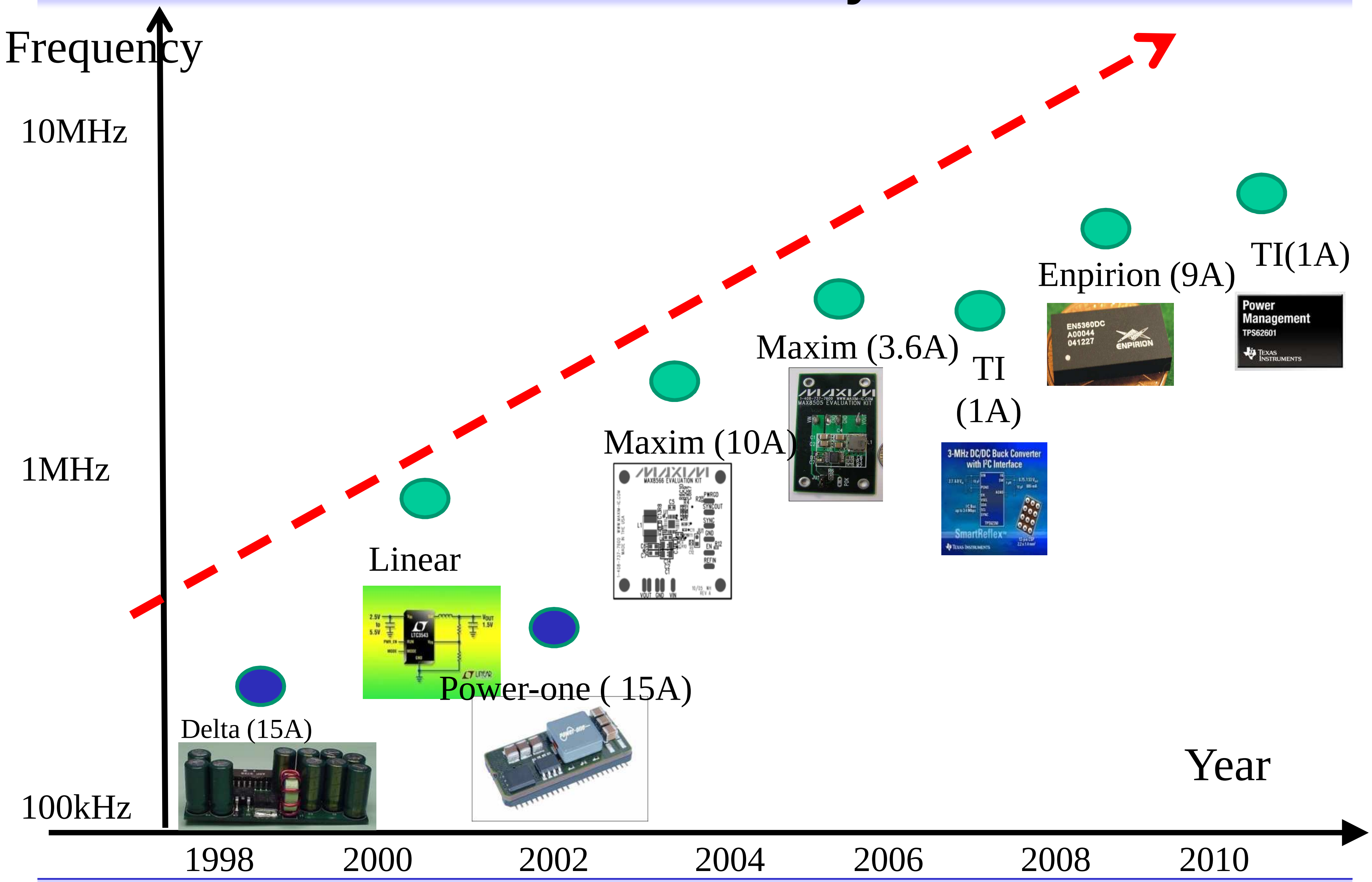
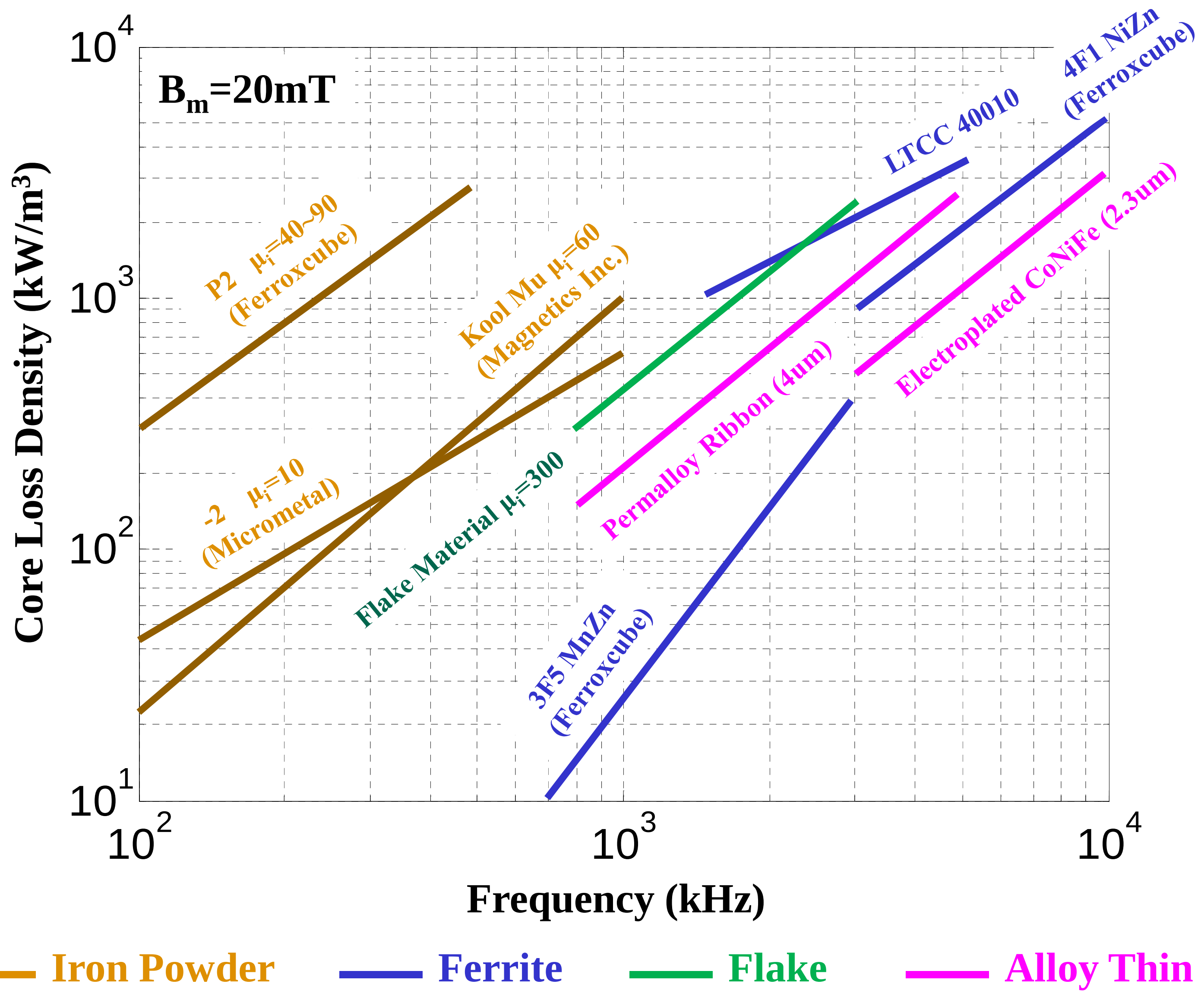
February 8, 2012

Increasing Frequency for High Power Density



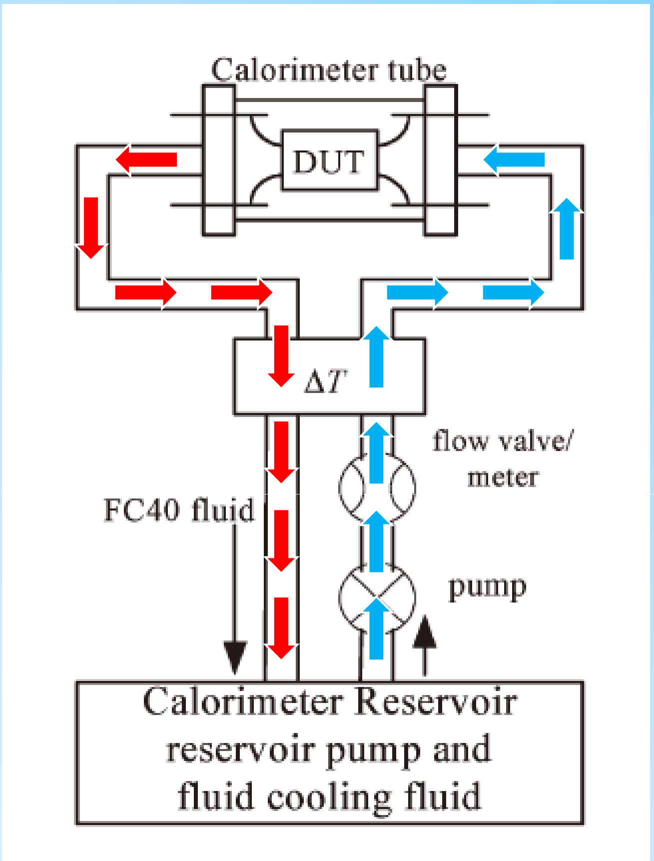
Core Loss Map for Magnetic Materials



Outlines

- Overview
- Existing core loss measurement methods
- Proposed core loss measurement methods
  - For sinusoidal excitations
  - For general excitations
- Conclusion

Core Loss Measurement Method I



Block Diagram of Closed Type Calorimeter

$$P = \frac{c_p \cdot m \cdot \Delta T}{dt}$$

➢**Pros**

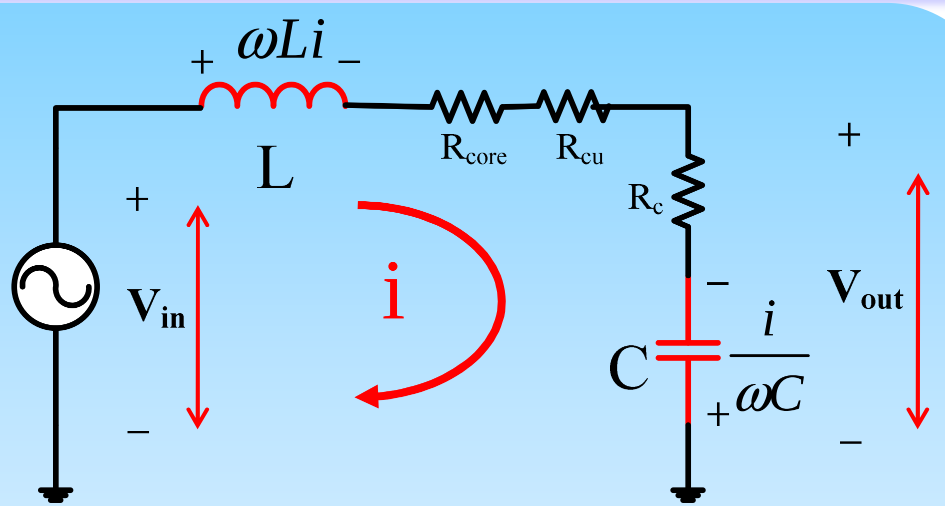
Arbitrary excitation

➢**Cons**

- **Setup is complex and time consuming.**
- **Not good for low power measurement**
- **If use winding to excite the core, winding resistance can be hardly separated.**

*Chucheng Xiao, Gang Chen and .G.Odendaal, "Overview of Power Loss Measurement Techniques in Power Electronics Systems", Industry Applications Conference, 2002

Core Loss Measurement Method II



Choose C to resonant with L at the measured frequency, so voltage on L and C cancel each other.

$$\frac{V_{out-pk}}{V_{in-pk}} = \left| \frac{R_c + \frac{1}{j\omega C}}{R_{core} + R_{cu} + R_c} \right| \approx \frac{1}{\omega C (R_{core} + R_{cu} + R_c)}$$

$$R_{core} \approx \frac{1}{\omega C} \frac{V_{in-pk}}{V_{out-pk}} - R_{cu} - R_c$$

➢**Pros.**

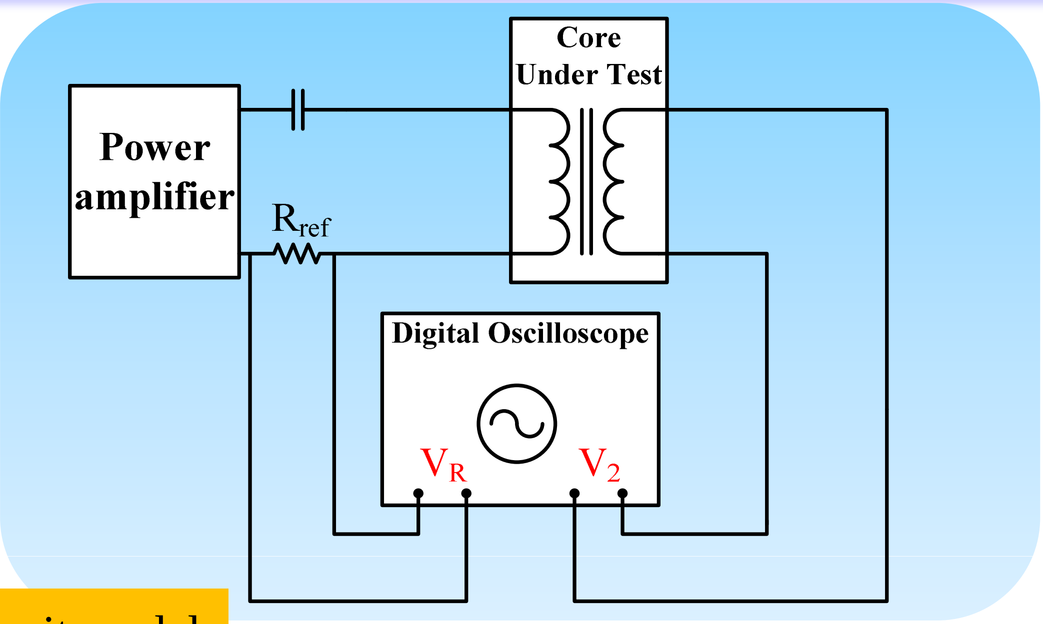
Minimize phase error.

➢**Cons.**

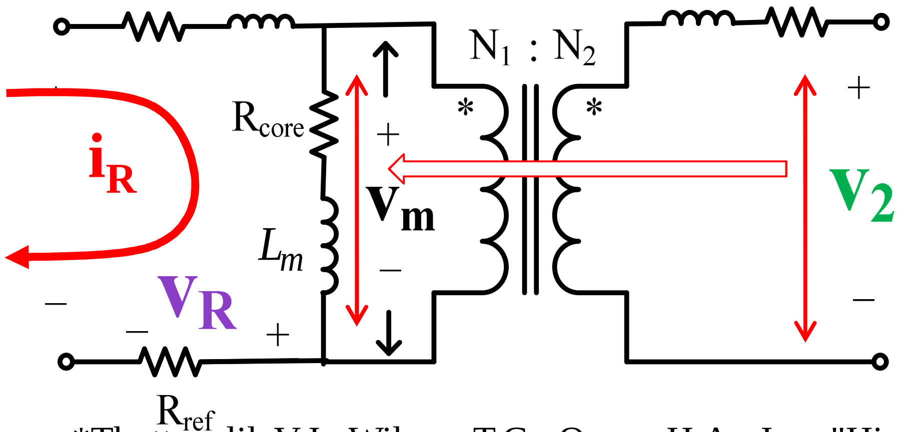
- **Hard to exclude winding loss**
- **C value is critical**
- **Sinusoidal waveform only**

*Yehui Han, Grace Cheung, An Li, Charles R. Sullivan† and David J. Perreault, "*Evaluation of Magnetic Materials for Very High Frequency Power Applications*", *Power Electronics Specialists Conference, 2008.*

Core Loss Measurement Method III



Equivalent Circuit model



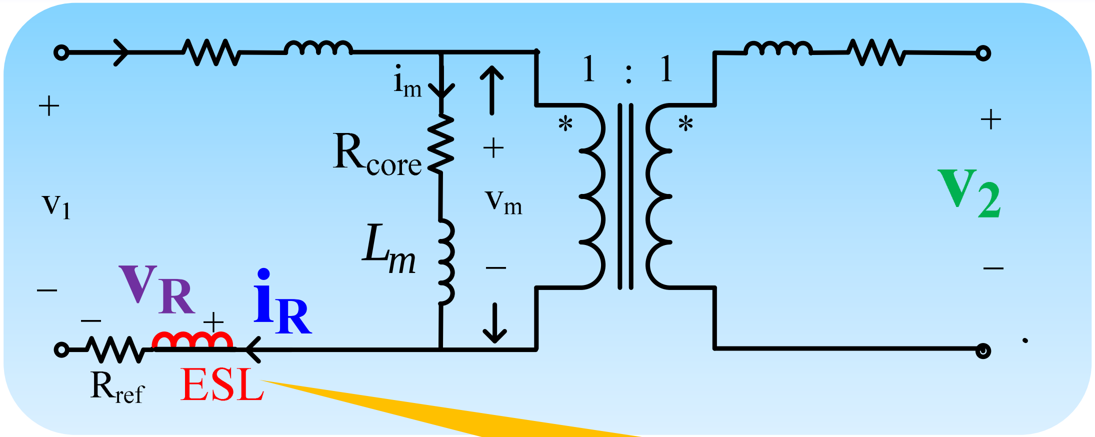
Calculation

$$B = \frac{1}{N_2 A_e} \int_T v_2(t)dt$$

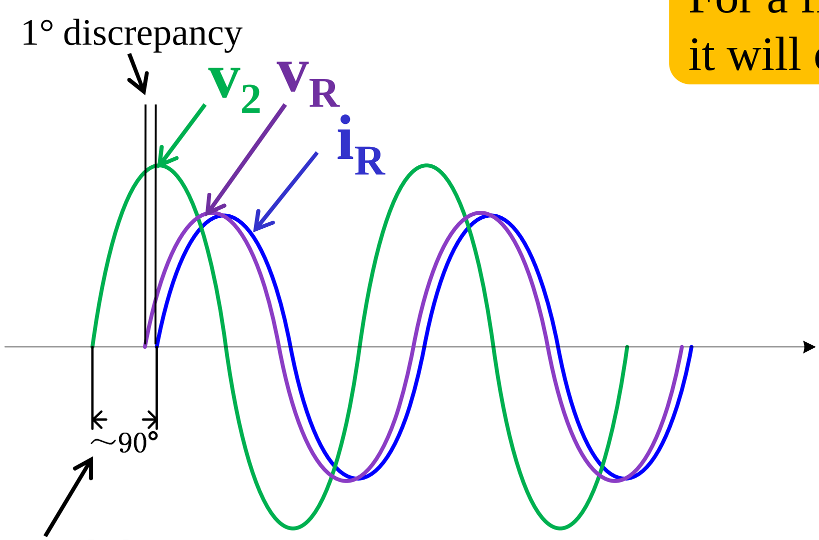
$$P_{core} = \frac{N_1 f}{N_2 R_{ref}} \int_T v_2(t) v_R(t) dt$$

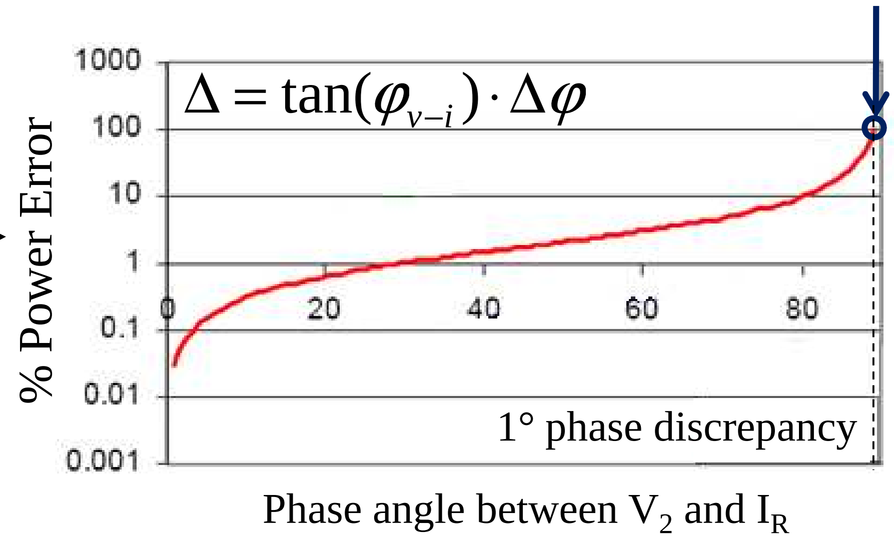
*Thottuvelil, V.J.; Wilson, T.G.; Owen, H.A., Jr.; , "High-frequency measurement techniques for magnetic cores," *Power Electronics, IEEE Transactions on* , vol.5, no.1, pp.41-53, Jan 1990

Limitation: Sensitivity to Phase Discrepancy

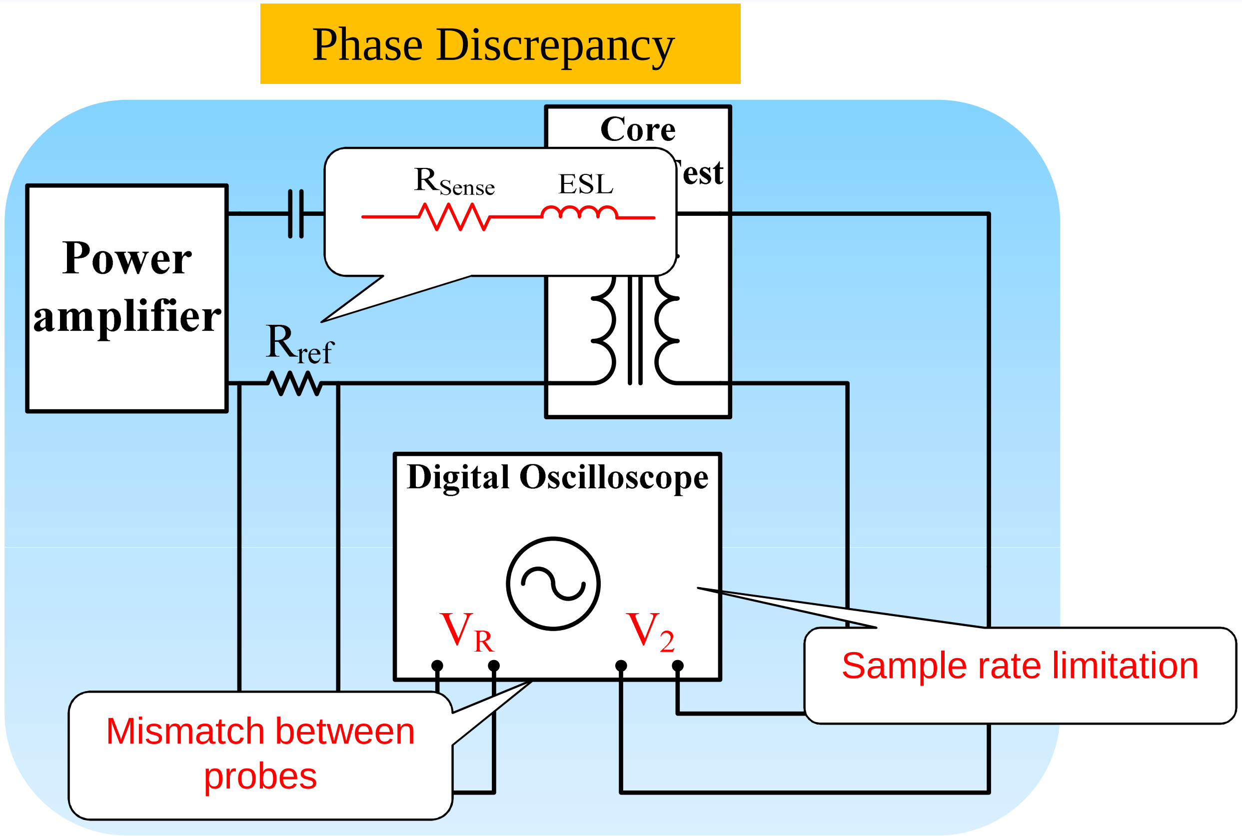


For a film resistor of 2 ohm, if the ESL is 0.5nH, it will cause 0.9° discrepancy at 5MHz.





Sources of Phase Discrepancy



➢Pros
- **Exclude winding loss.**
- **Arbitrary waveform.**

➢Cons
- **Sensitive to phase error. So not suitable for high frequency core loss measurement**

Outlines

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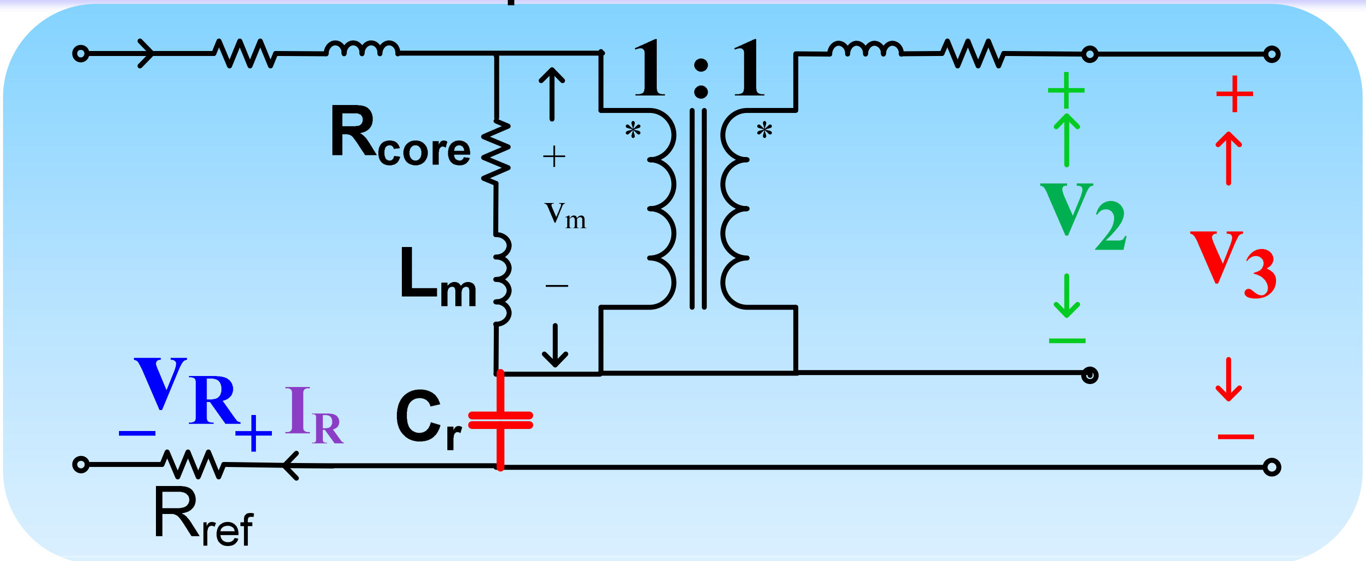
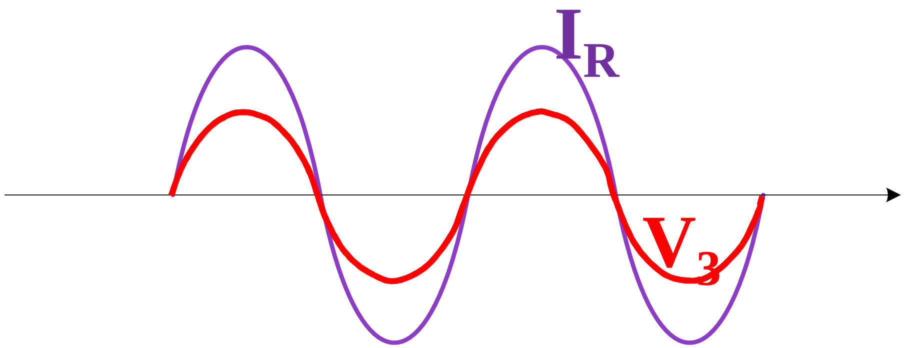
Proposed New Method I
-- capacitive cancellation





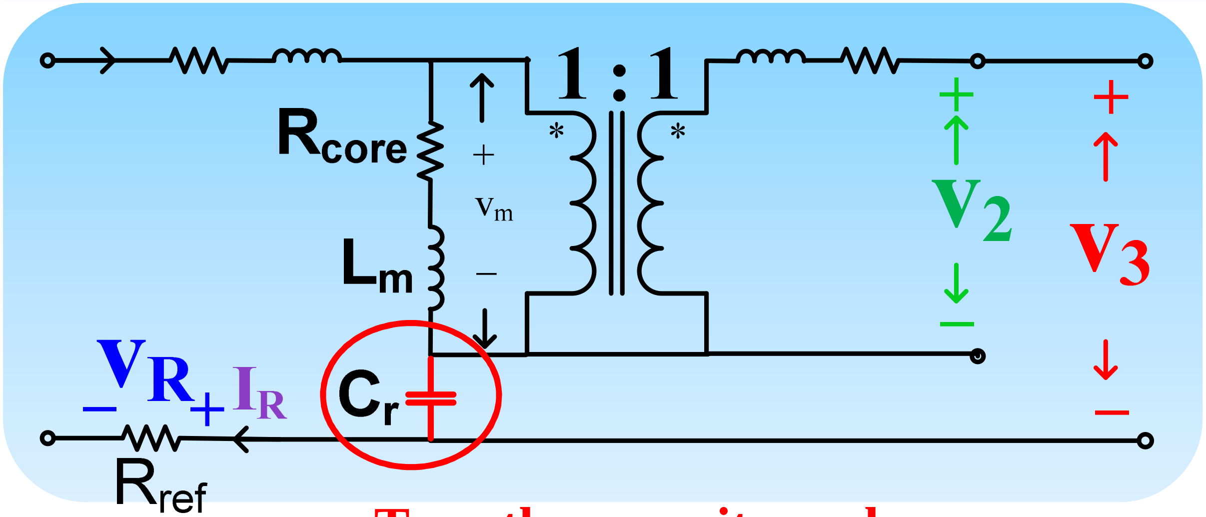
$$V_3 = (R_{core} + j\omega L_m - j\frac{1}{\omega C_r})I_R$$

$$P_{core} = \frac{1}{T}\int_0^T V_3 I_R \, dt$$

C_r is used to cancel the observed reactive voltage seen by the probe.

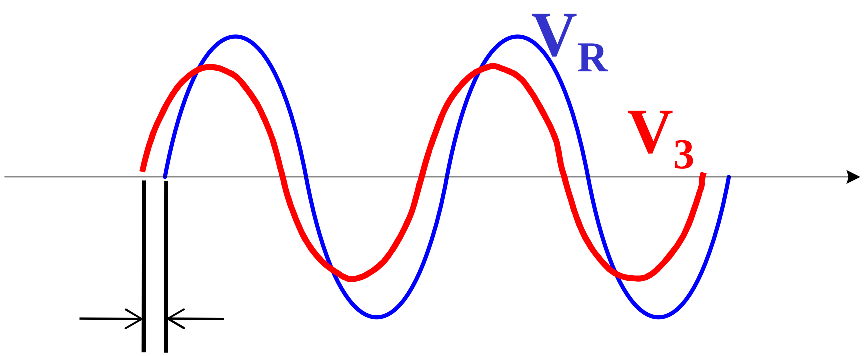
* Mingkai Mu, Qiang Li, David Gilham, Fred C. Lee, Khai D.T. Ngo, "New core loss measurement method for high frequency magnetic materials", Energy Conversion Congress and Exposition, Sept. 2010, pp. 4384 – 4389.

Proposed New Method I (cont')
-- capacitive cancellation

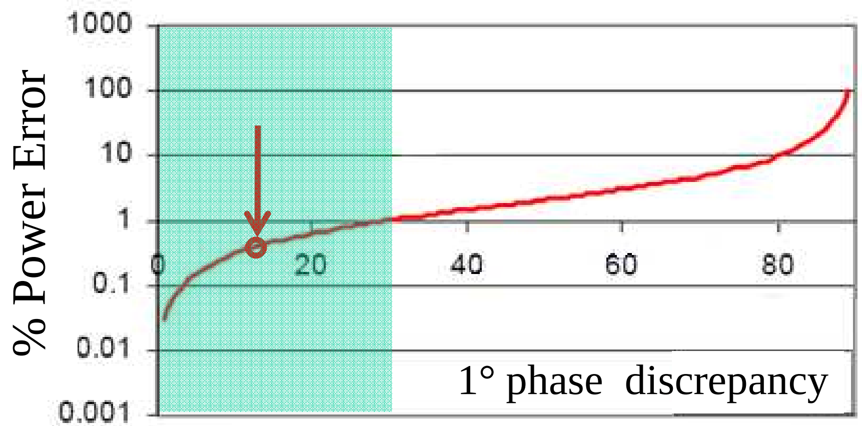


$$P_{core} = \frac{1}{TR_{ref}} \int_0^T v_3 v_R \, dt$$

Tune the capacitor value



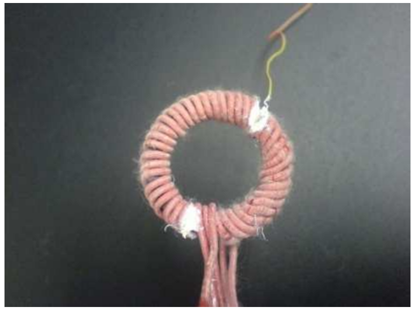
Phase angle



Phase angle between V_3 and I_R

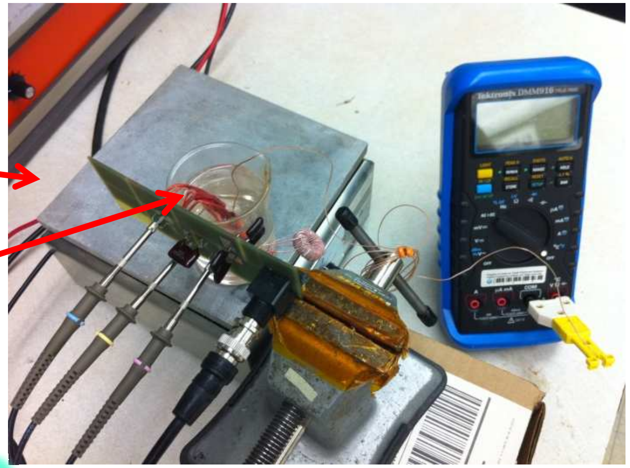
Given 1 ° phase discrepancy, 30° phase angle is enough to reduce phase error below 1%

Measurement Setup



Core material: NiZn ferrite (4F1)
Number of Turns: 14:14
Core Cross section area: $A=5.98*10^{-6}m^2$
Average flux path length: l=7.19 cm
Osc-scope: Tek TDS7054

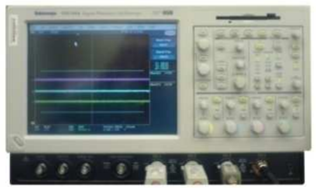
Hot plate



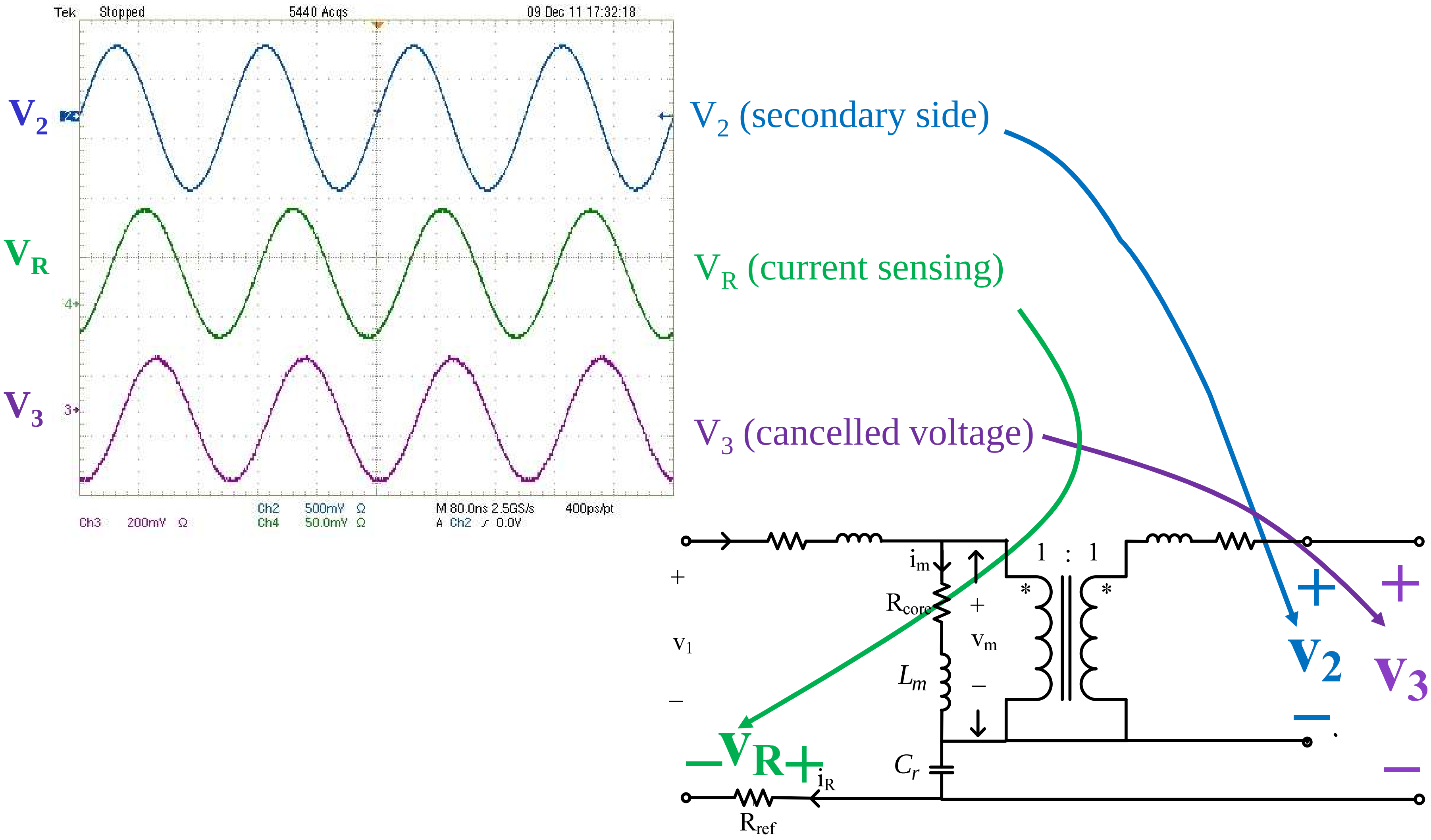
core under test immersed in thermal oil

Power Input

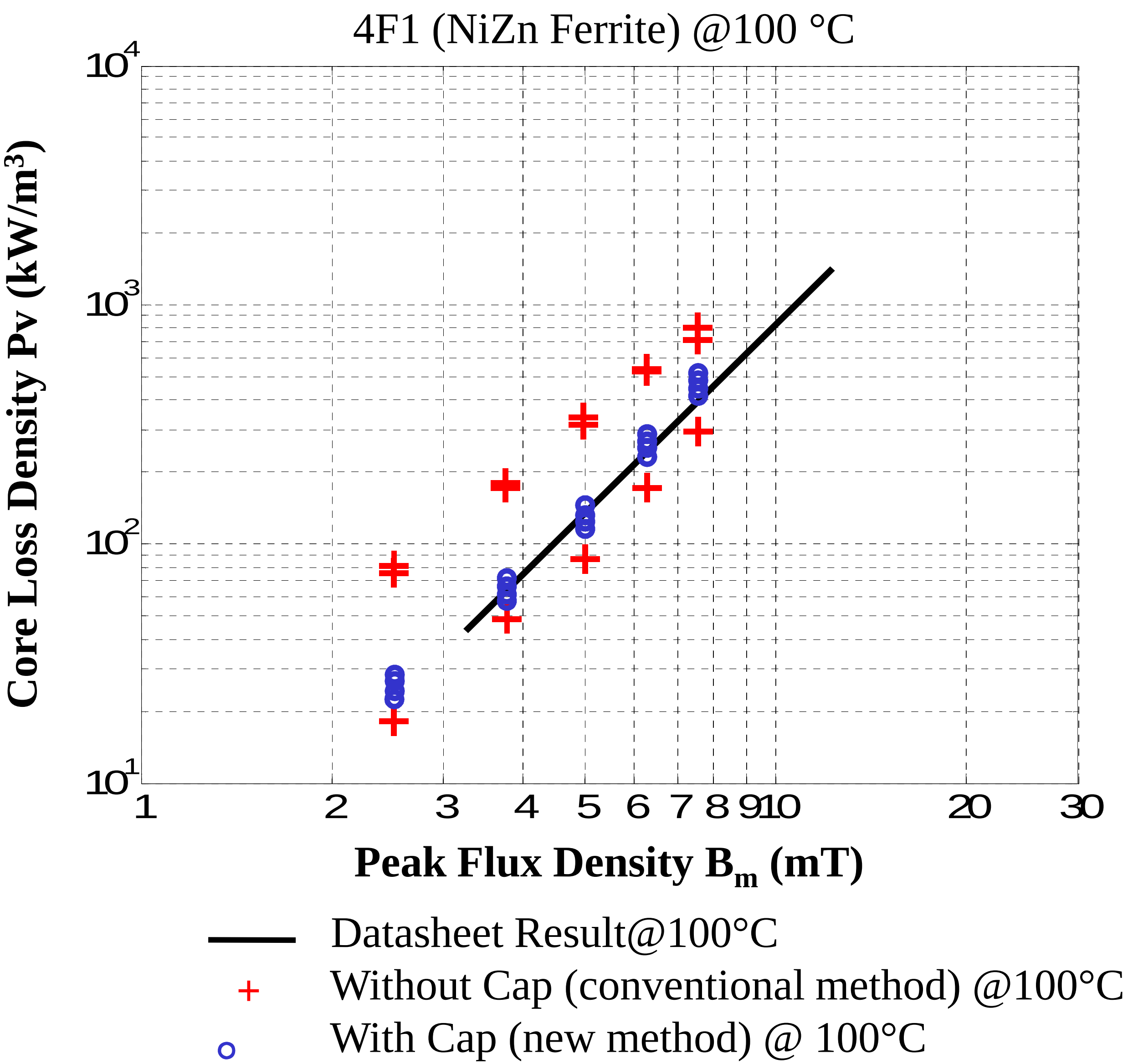
Oscilloscope



Working Waveform



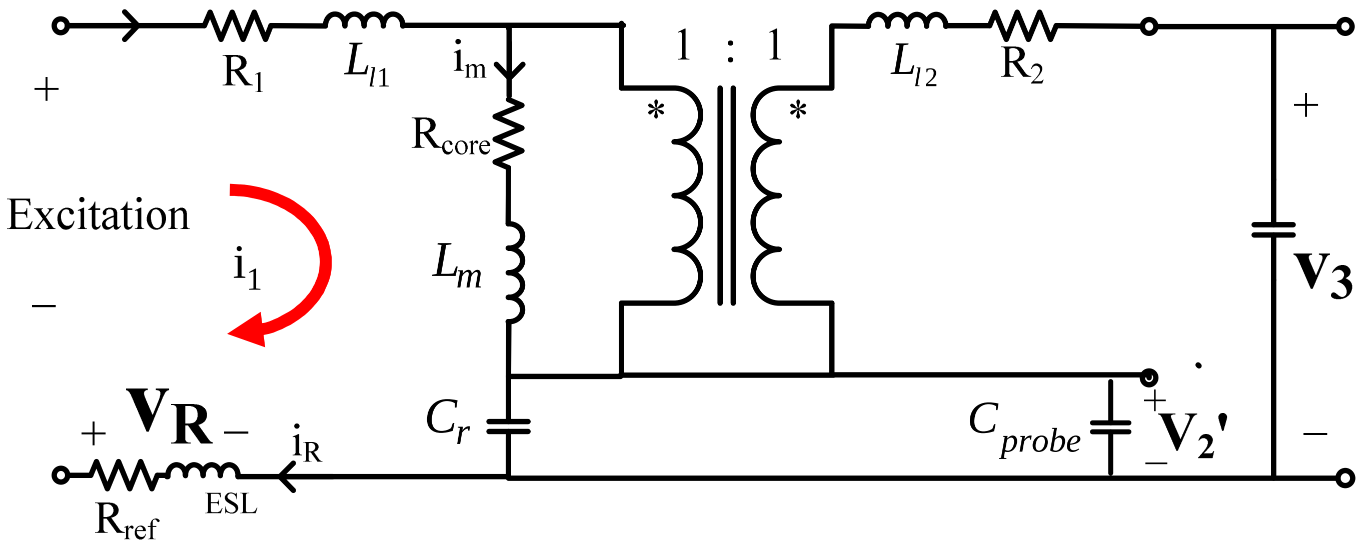
Measurement Result @ 10MHz



Factors May Influence Accuracy

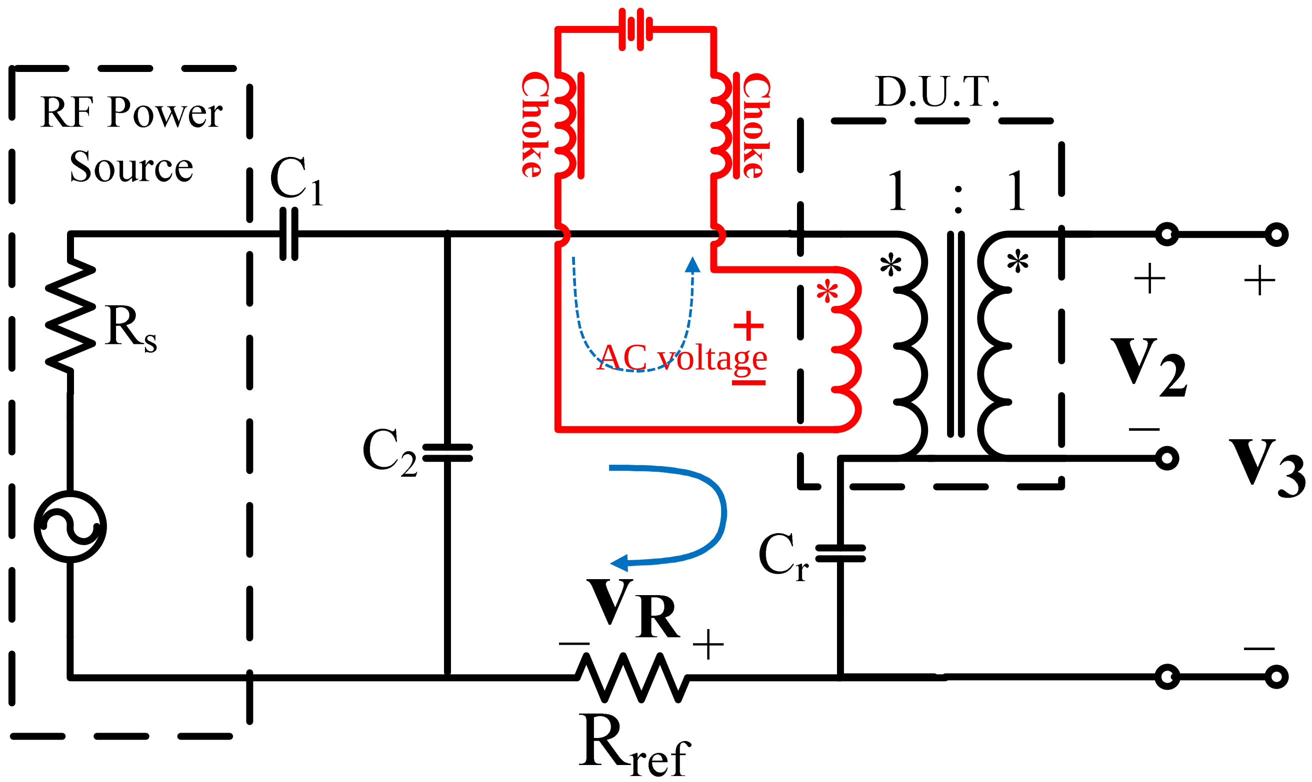
- **Phase Error**
  - This error can be minimized when C_r resonates at excitation frequency.
- **Resonant Cap ESR**
  - An additional resistor is in series with the R_c, L_m, C branch.
- **Parasitic Capacitor**
  - These parasitic capacitors (inter- and intra-winding capacitor and probe loading effect) will introduce a small current on the secondary side.

Improved Circuit to Reduce the Probe Loading Effect



Measure the voltage on resonant cap, instead of the voltage of transformer's secondary. So it merges the parasitic cap into the resonant cap, and has less loading effect by probe input cap.

Test Setup with DC Bias Field

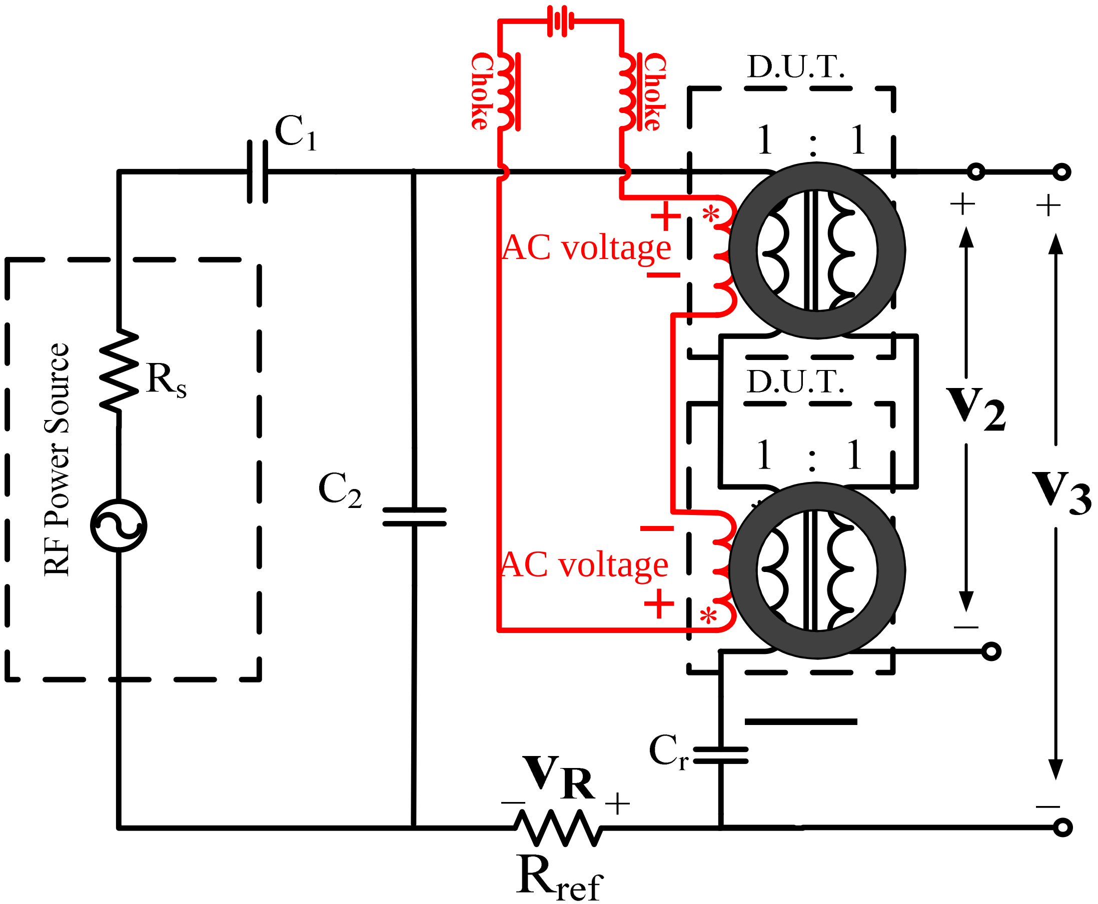


Add Winding for DC Pre-magnetization

Two Choke inductance should be large enough to block AC current

$$2L_{choke} >> L_m$$

Improved Scheme

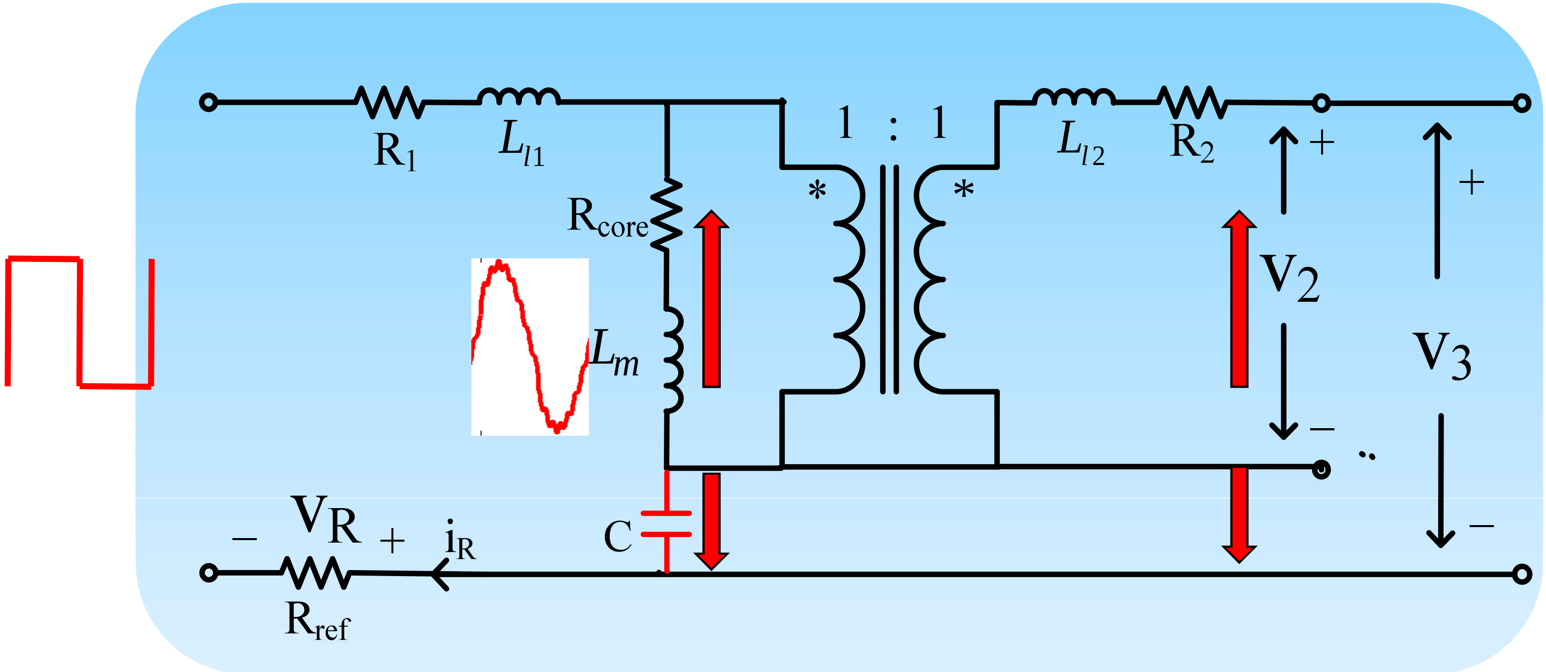


The AC voltage seen by the DC current source is minimized.

Yongtao Han, Yan-Fei Liu, "A Practical Transformer Core Loss Measurement Scheme for High-Frequency Power Converter", IEEE Transactions on Industrial Electronics, 2008, pp. 941-948.

Mingkai Mu, Yipeng Su, Qiang Li, Fred C. Lee, "Magnetic Characterization of Low Temperature Co-fired Ceramic (LTCC) Ferrite Materials for High Frequency Power Converters", Energy Conversion Congress and Exposition, Sept. 2011, pp. 2133 - 2138.

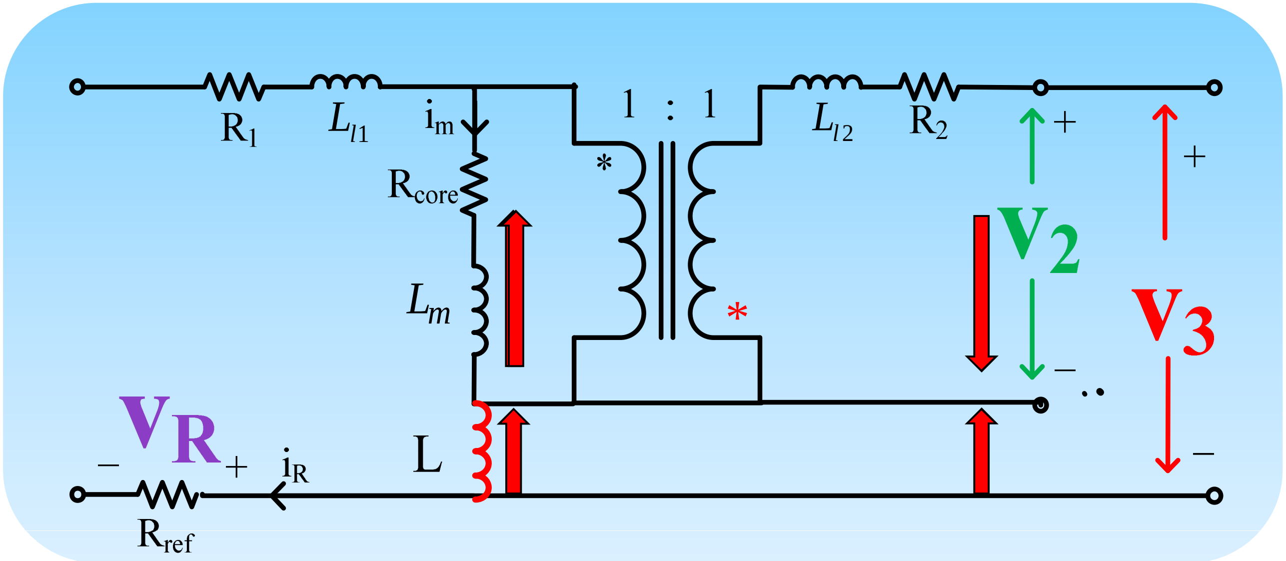
Limited for Sinusoidal Excitation

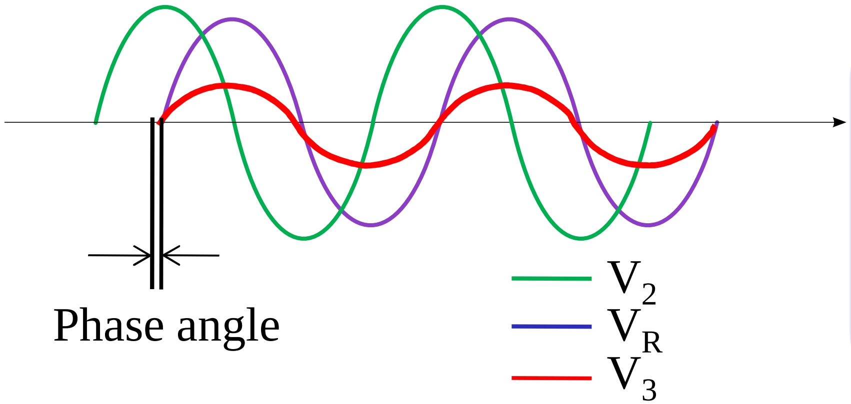


$$V_3 = (R_{core} + j\omega L_m - j\frac{1}{\omega C_r})I_R$$

The capacitor can only cancel the reactive voltage at a single frequency.

Proposed New Method II
-- Inductive Cancellation





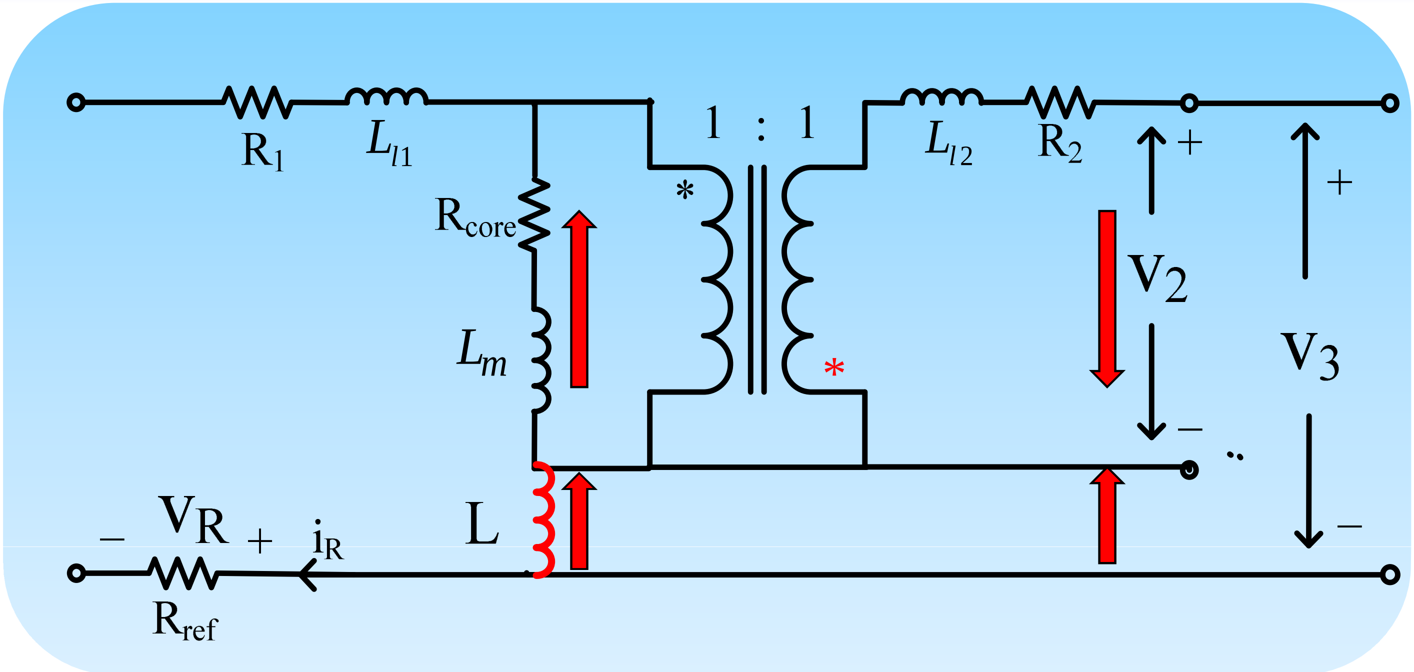
$$V_3 = (-R_{core} - j\omega L_m + j\omega L)I_R$$

$$P_{core} = \frac{N_1 f}{N_2 R_{ref}} \int_T v_3 v_R \, dt$$

Using inductor, we can still cancel the observed reactive voltage.

Mingkai Mu, Fred C. Lee, Qiang Li, David Gilham, Khai D.T. Ngo, "A high frequency core loss measurement method for arbitrary excitations", Applied Power Electronics Conference, 2011, pg.157-162.

Proposed Method II (cont')
-- Compatible with Arbitrary Waveform

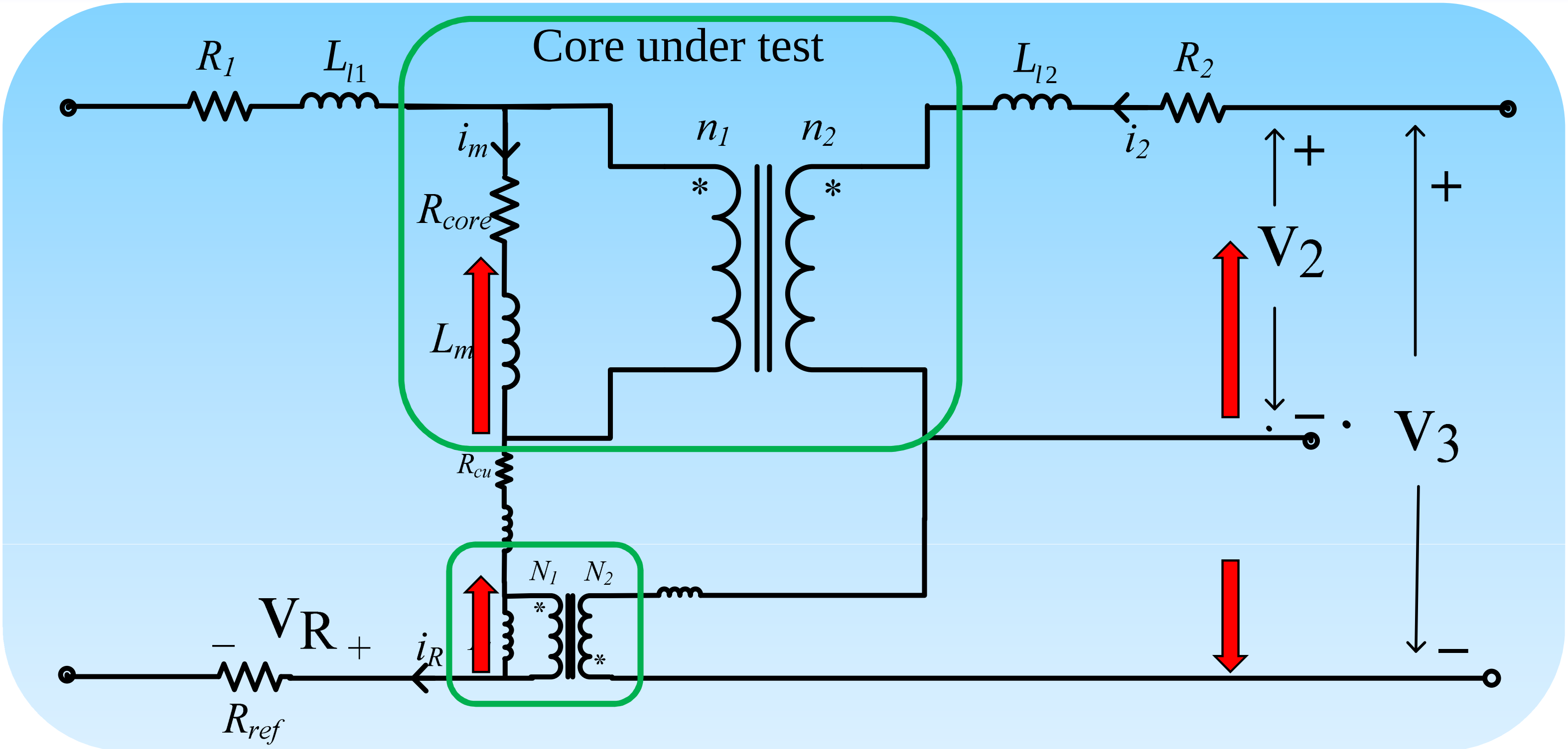


$$V_3 = (-R_{core} - j\omega L_m + j\omega L)I_R$$

When L = L_m, the reactive voltage is cancelled out, leaving only the voltage on resistor.

For this method, a high Q inductor is needed in order to reduce the error introduced by the loss of the inductor.

Using Air Core or Low-loss Core Transformer's Magnetizing Inductor

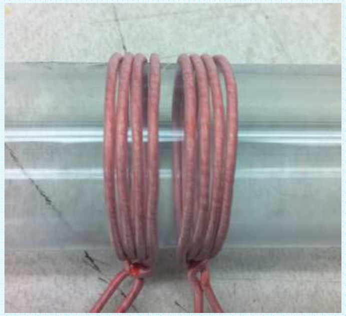


Air core transformer or Low core loss transformer

Using the magnetizing inductance of air core or low loss core to eliminate the error caused by winding resistance.

From another perspective, the principle is to compare the core loss of DUT with the reference core.

Reference Core



Choice 1: Air core

Advantage: no core loss

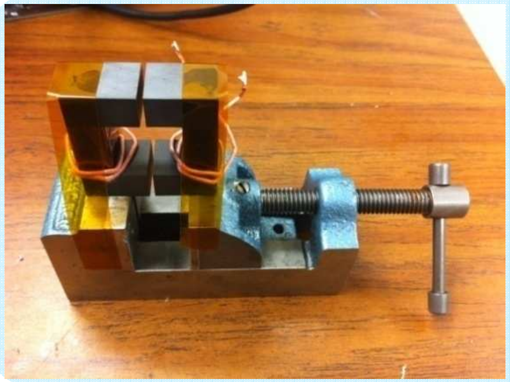
Disadvantage: larger parasitic capacitance and inductance

Choice 2: Low loss core

Advantage: smaller parasitics

Disadvantage: hard to find if measure low loss material

not convenient to adjust inductance value.



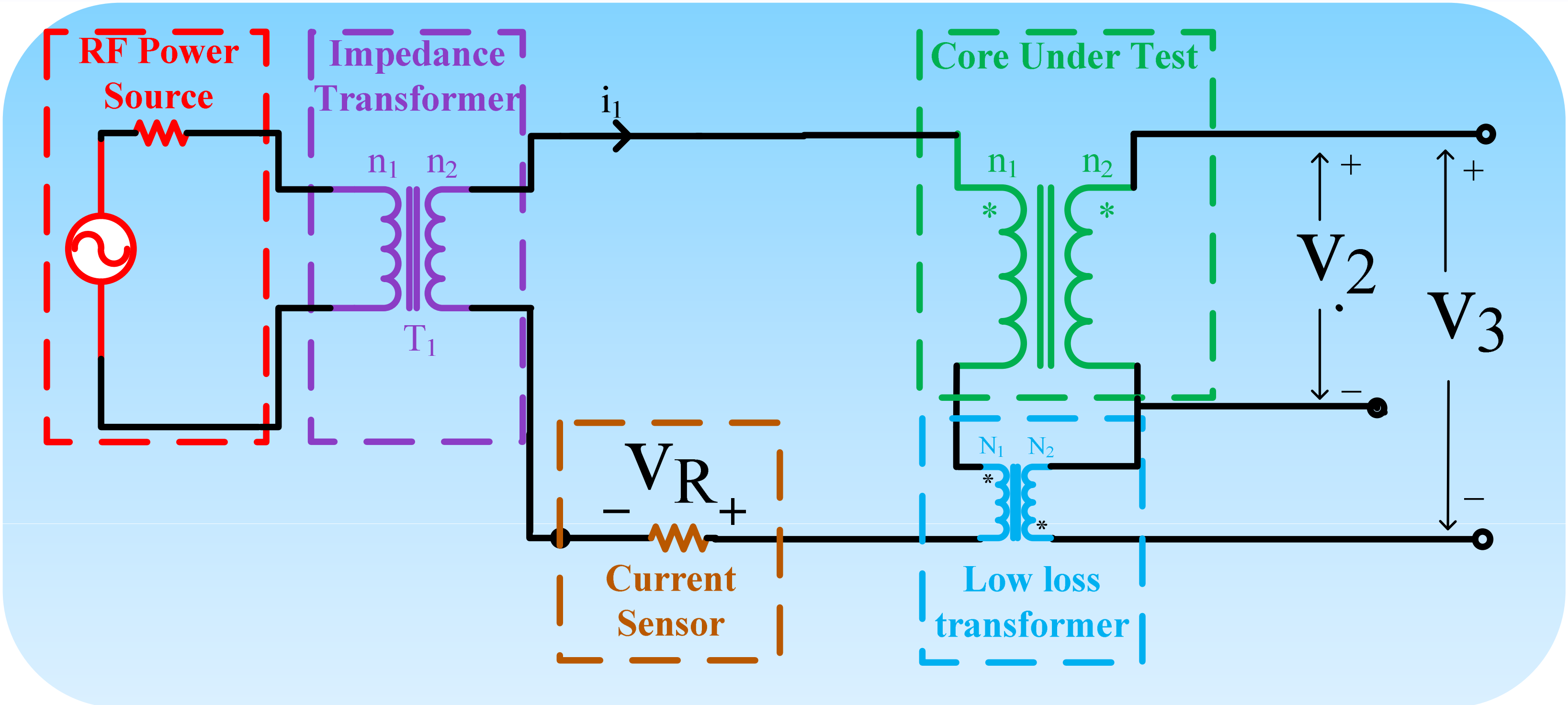
Choice 3: Low loss core with adjustable air gap

Advantage: smaller parasitics

easy to adjust inductance value

Disadvantage: hard to find if measure low loss material

Excitation



The circuit is excited by the function generator signal amplified by power amplifier.

The power amplifier has 50Ω internal impedance, so an impedance transformer is needed to reduce the voltage drop on the internal impedance.

Programmable function generator is used to generate desired waveforms.

Test Example
Core-under-test and Reference Core

LTCC 40011 (ESL®) Core sample

4F1 (Ferroxcube®) Reference

Toroid LTCC 40011

n_1:n_2=10:10

A_e=3.82mm^2

l_e=64.5mm

v_e=246.4mm^3

Toroid 4F1

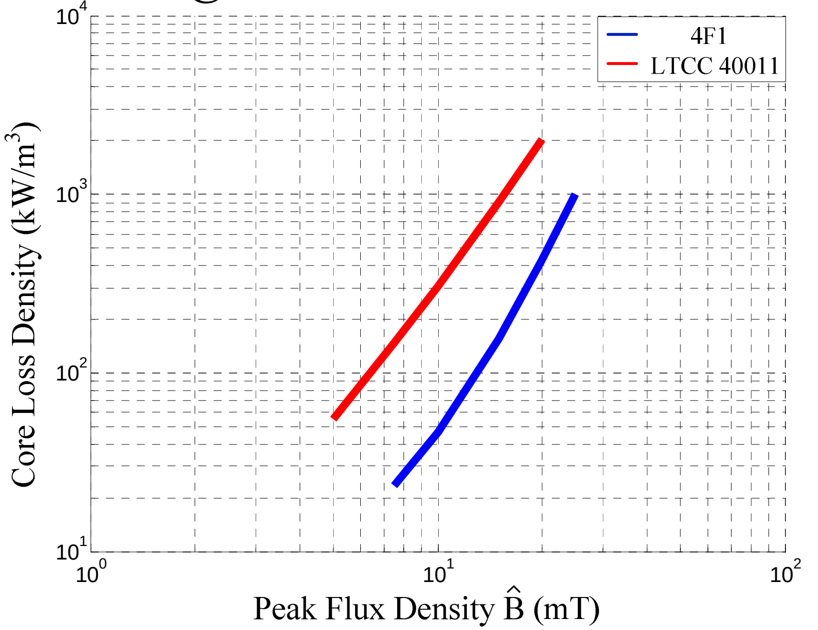
N_1:N_2=9:9

A_e=11.88mm^2

l_e=24.5mm

v_e=291mm^3

Core Loss @ 1.5MHz Sinusoidal Excitation*



$$\frac{B_{LTCC}}{B_{4F1}} = \frac{\frac{1}{n_1 A_{eLTCC}} \int v_{LTCC} dt}{\frac{1}{N_1 A_{e4F1}} \int v_{4F1} dt} = 2.8$$

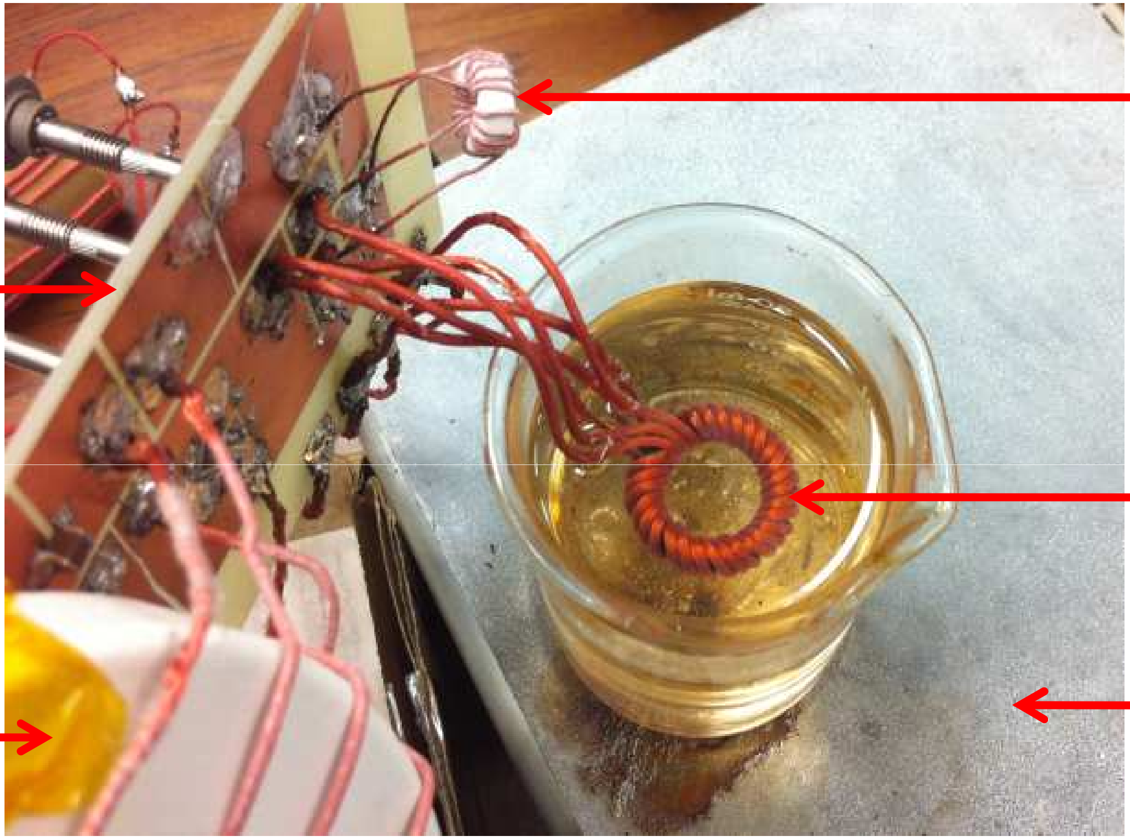
Core loss in 4F1 core is much smaller than LTCC 40011.

*The core loss data is measured using the capacitive cancellation.

Measurement Setup

Test circuit

Impedance transformer



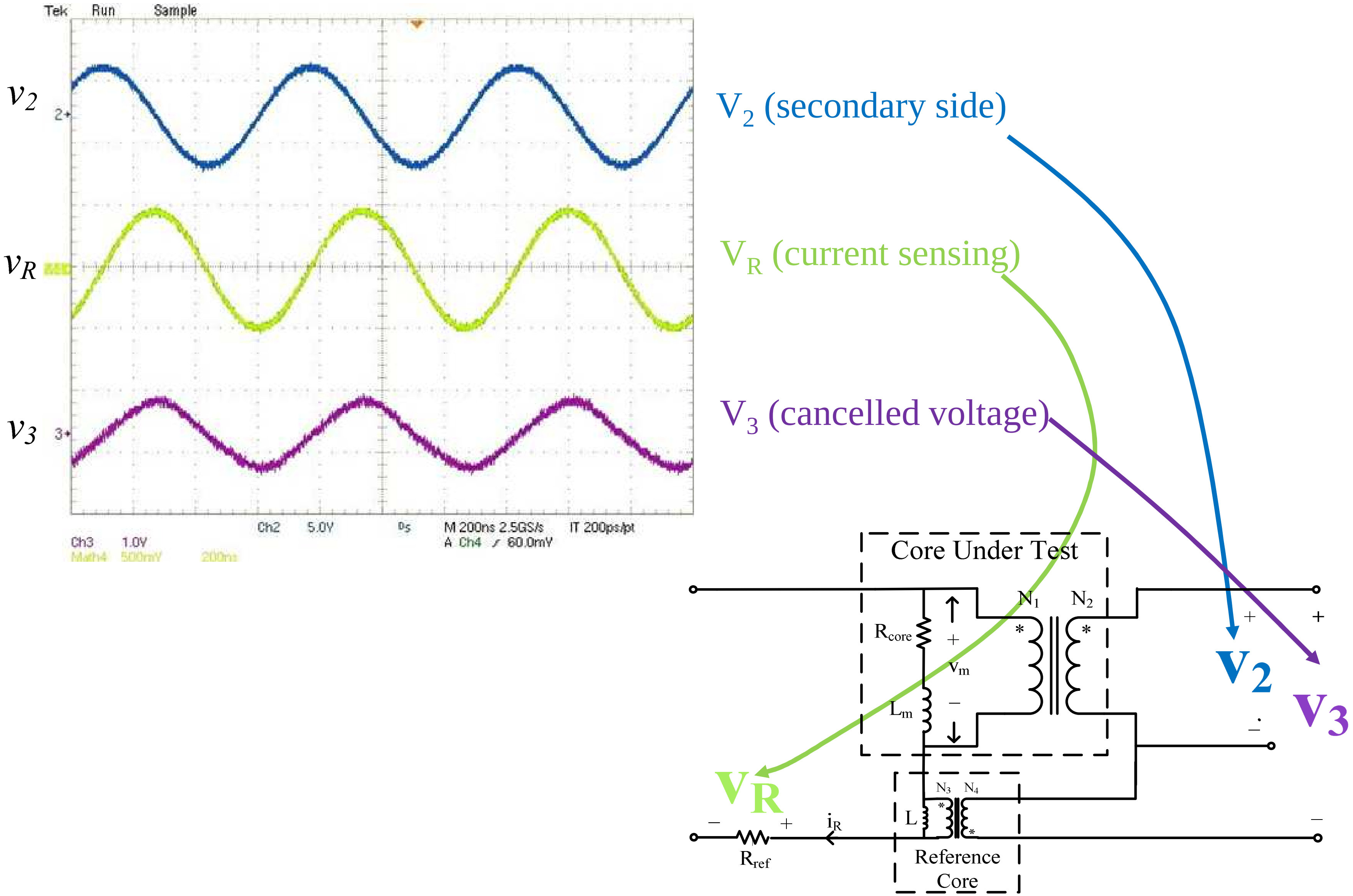
4F1

LTCC 40011 in oil bath

Hot plate

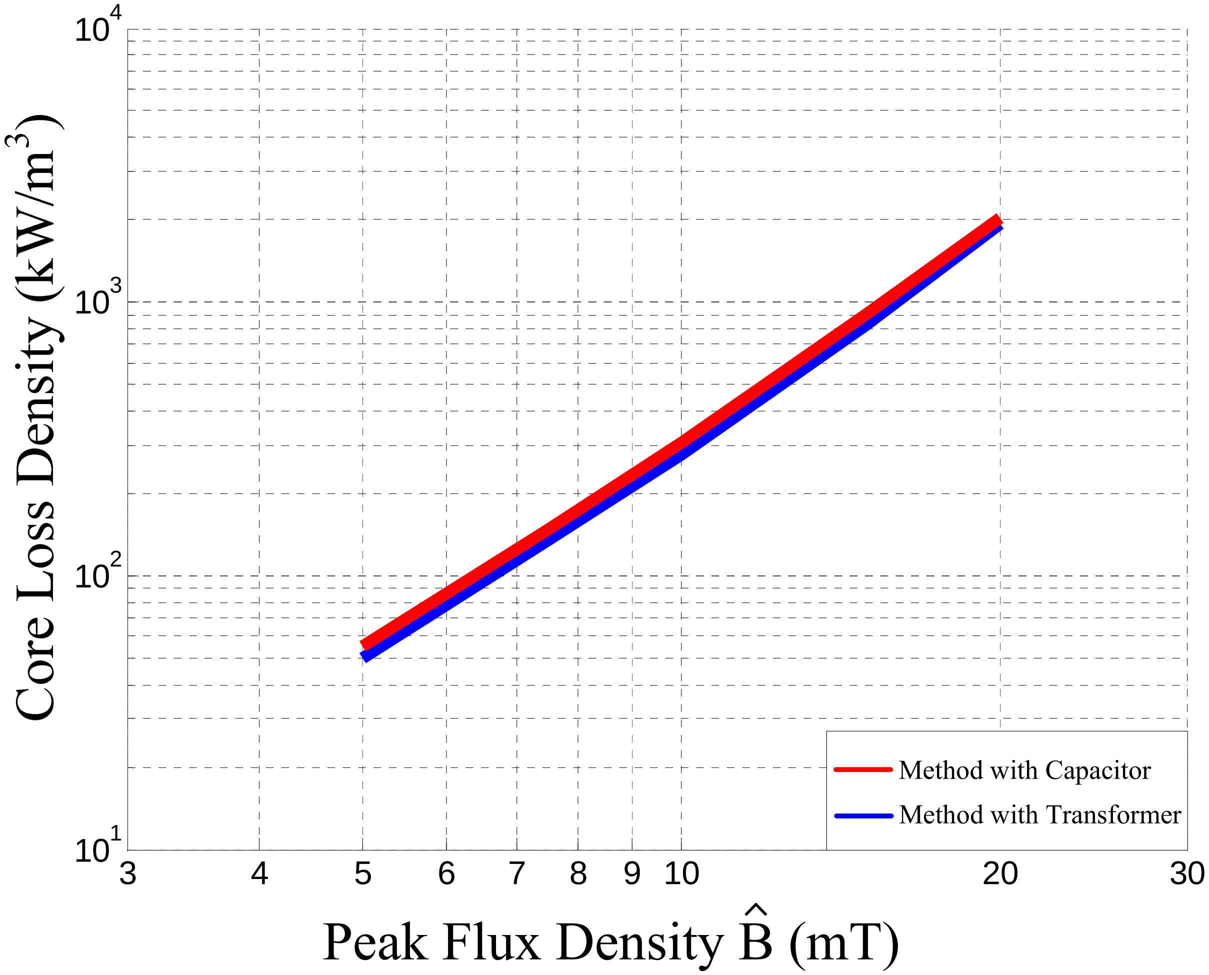
Test LTCC 40011 using 4F1

Measurement Waveforms
Sinusoidal Voltage



Core Loss of Sinusoidal Excitation

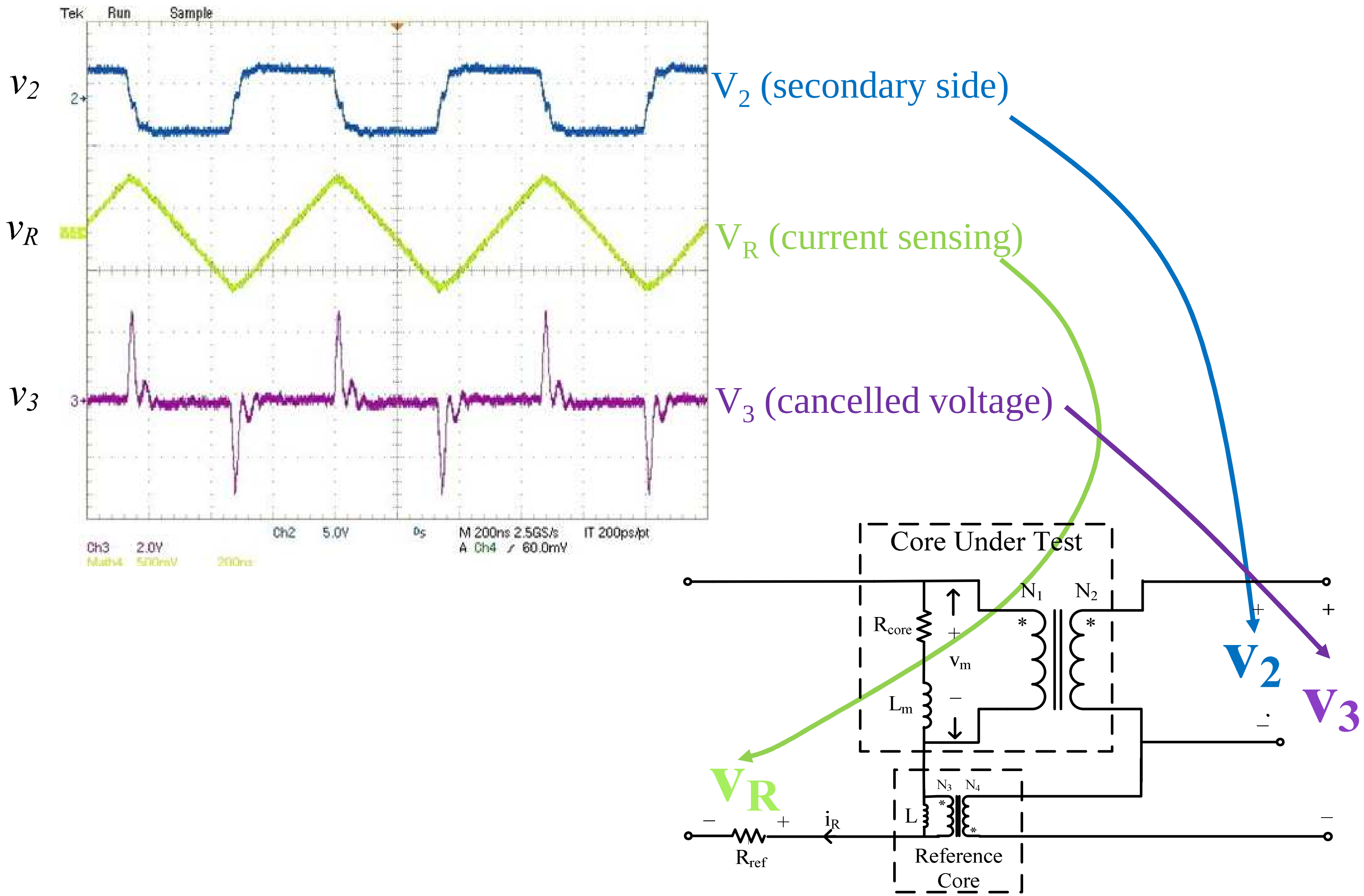
Measured core loss with capacitive and inductive cancellation



*1.5MHz, 100°C

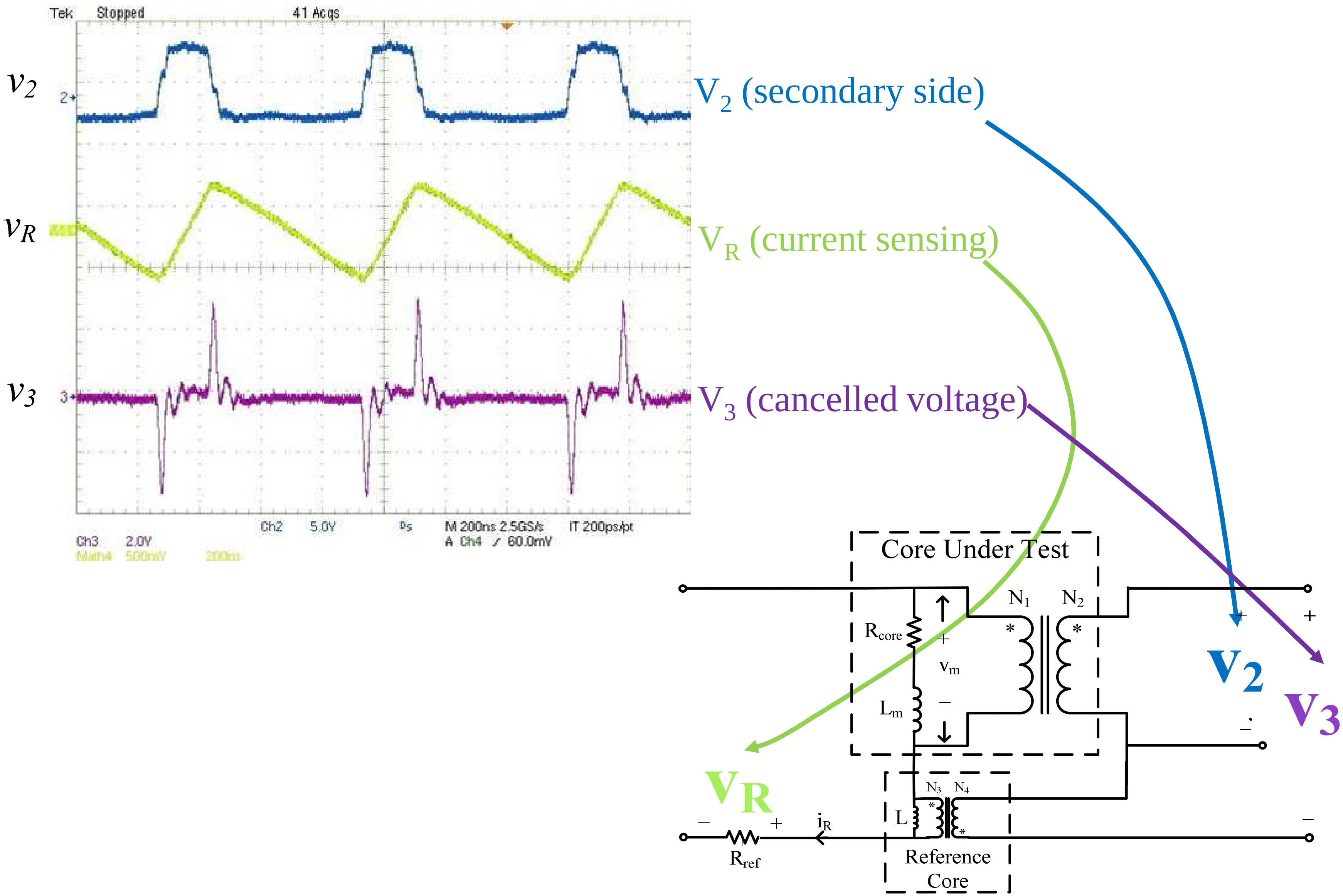
Measurement Waveforms

Rectangular Voltage (50% Duty Cycle)



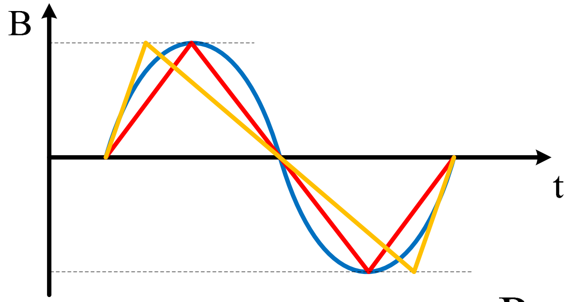
Measurement Waveforms

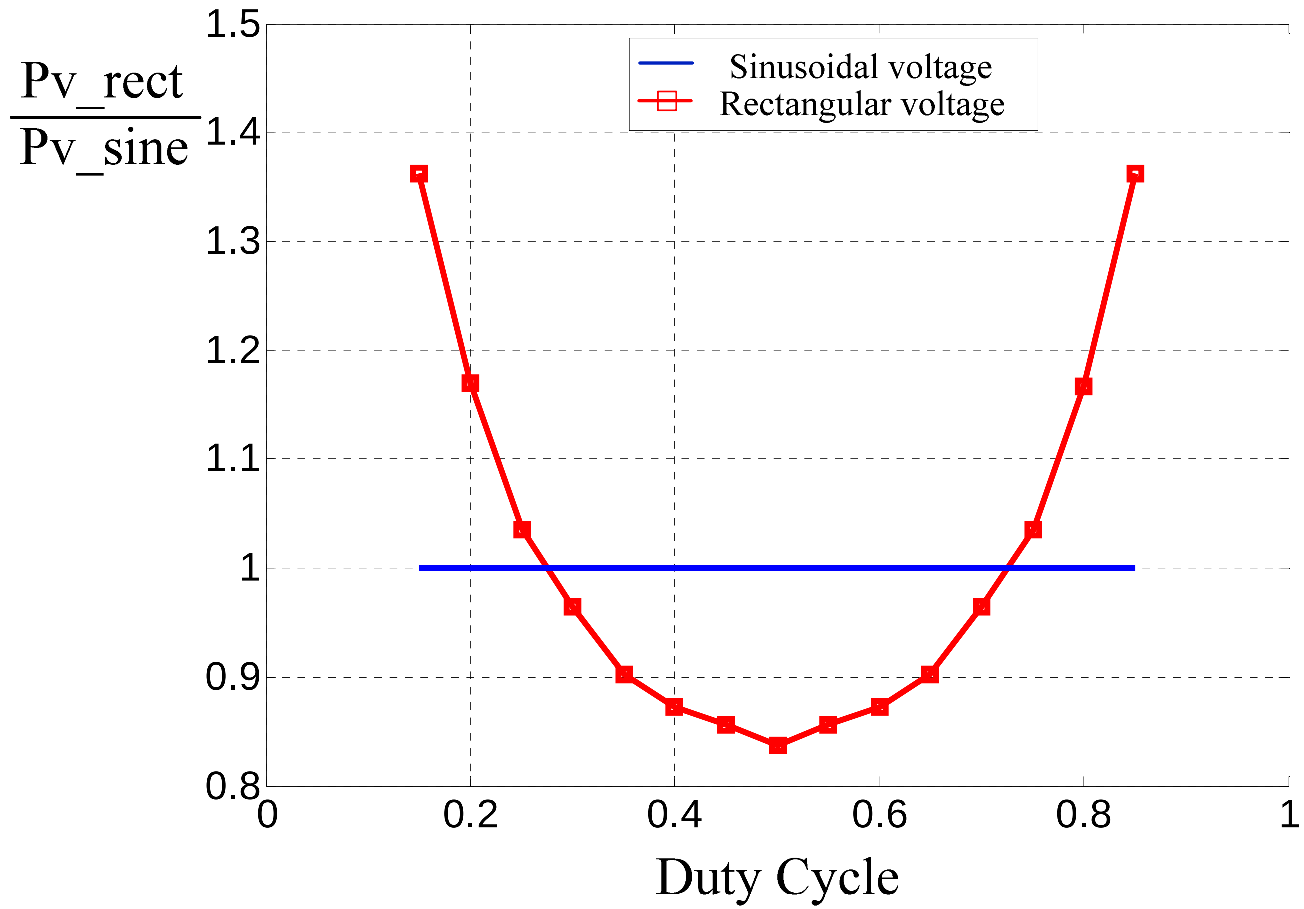
Rectangular Voltage (25% Duty Cycle)



Core Loss of LTCC 40011

Rectangular Voltage Waveforms of Different Duty Cycles





Conclusion

- A new series of high frequency core loss measurement methods are proposed, which excludes winding loss and reduce phase discrepancy sensitivity.

- The principle is using capacitor or inductor to cancel the reactive voltage seen by the probe to reduce the sensitivity to phase error. The capacitor version is good for sinusoidal excitation; the inductor version is broad-band, so it can measure the core loss of general waveforms.

Conclusion (cont')

- For capacitor version, high Q capacitor is needed to reduce the ESR induced error. For inductor version, the reference core is important for this measurement. Air core, low loss core or air gapped core should be selected according to the core under test. Adjustable capacitor or transformer will make the measurement more easier.

- With this new series of methods, high frequency core loss can be accurately measured at different excitations. The core loss measurement problem can be addressed for power electronics applications and material science research.

Q & A

Thank you!

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