A New Series of High Frequency Core Loss Measurement Methods

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Increasing Frequency for High Power Density

Frequency

10MHz

1MHz

100kHz

Year


1MHz 100kHz

Linear (8A)

Delta (15A)

Power-one (15A)

Maxim (10A)

Maxim (3.6A)

Ti (1A)

Enpirion (9A)

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Core Loss Map for Magnetic Materials

$B_m = 20 \text{mT}$

Iron Powder
Ferrite
Flake
Alloy Thin Film

Core Loss Density ($\text{kW/m}^3$)

Frequency (kHz)

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Outlines

• Overview
• Existing core loss measurement methods
• Proposed core loss measurement methods
  – For sinusoidal excitations
  – For general excitations
• Conclusion
Core Loss Measurement Method I

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

**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.

Block Diagram of Closed Type Calorimeter

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

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

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

**Pros.**
- Minimize phase error.

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

Core Loss Measurement Method III

Equivalent Circuit model

Calculation

\[ B = \frac{1}{N_2 A_e} \int v_2(t) dt \]

\[ P_{\text{core}} = \frac{N_1 f}{N_2 R_{\text{ref}}} \int v_2(t) v_R(t) dt \]

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.

\[ \Delta = \tan(\varphi_{v-i}) \cdot \Delta \varphi \]

\( \Delta \) Power Error

Phase angle between \( V_2 \) and \( I_R \)

Phase angle between \( V_2 \) and \( I_R \)

1° discrepancy

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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

- Overview
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- Proposed core loss measurement methods
  - For sinusoidal excitations
  - For general excitations
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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.
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

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: $A=5.98 \times 10^{-6} \text{m}^2$
Average flux path length: $l=7.19 \text{ cm}$
Oscilloscope: Tek TDS7054

Hot plate

Core under test immersed in thermal oil

Power Input

Oscilloscope
Measurement Result @ 10MHz

Core Loss Density $P_v$ (kW/m$^3$) vs. Peak Flux Density $B_m$ (mT)

- **Datasheet Result @ 100°C**
- **Without Cap** (conventional method) @ 100°C
- **With Cap** (new method) @ 100°C
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

$$2L_{\text{choke}} \gg L_m$$
The AC voltage seen by the DC current source is minimized.


The capacitor can only cancel the reactive voltage at a single frequency.
Proposed New Method II
-- Inductive Cancellation

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

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

\[ P_{\text{core}} = \frac{N_1 f}{N_2 R_{\text{ref}}} \int_T V_3 V_R dt \]


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

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

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

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

\( \omega \)
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
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®) 4F1 (Ferroxcube®)
Core sample Reference

Toroid LTCC 40011 Toroid 4F1
n₁:n₂=10:10 N₁:N₂=9:9
Aₑ=3.82mm² Aₑ=11.88mm²
lₑ=64.5mm lₑ=24.5mm
vₑ=246.4mm³ vₑ=291mm³

Core Loss @ 1.5MHz Sinusoidal Excitation*

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

*The core loss data is measured using the capacitive cancellation.
Test LTCC 40011 using 4F1
Measured core loss with capacitive and inductive cancellation

Core Loss Density (kW/m³)

Peak Flux Density $\hat{B}$ (mT)

Method with Capacitor
Method with Transformer

*1.5MHz, 100°C
Measurement Waveforms
Rectangular Voltage (50% Duty Cycle)

\[ V_2 \text{ (secondary side)} \]
\[ V_R \text{ (current sensing)} \]
\[ V_3 \text{ (cancelled voltage)} \]
Measurement Waveforms
Rectangular Voltage (25% Duty Cycle)

V_2 (secondary side)

V_R (current sensing)

V_3 (cancelled voltage)
Core Loss of LTCC 40011
Rectangular Voltage Waveforms of Different Duty Cycles

\[ \frac{P_{v_{\text{rect}}}}{P_{v_{\text{sine}}}} \]

- \( P_{v_{\text{rect}}} \): Rectangular voltage
- \( P_{v_{\text{sine}}} \): Sine voltage

Duty Cycle

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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.
Thank you!

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