Survey of Core Loss Test Methods

Prof. Charles R. Sullivan
chrs@dartmouth.edu

Dartmouth Magnetics and Power Electronics Research Group

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

http://power.engineering.dartmouth.edu

Core loss testing: difficult and important

- Nonlinear behavior requires:
  - Large-signal testing
  - Testing with bias
  - Understanding or testing the influence of the waveform shape.
- High *Q* (low-loss) measurements are difficult.
  - Especially at high frequency.

Types of core loss measurements

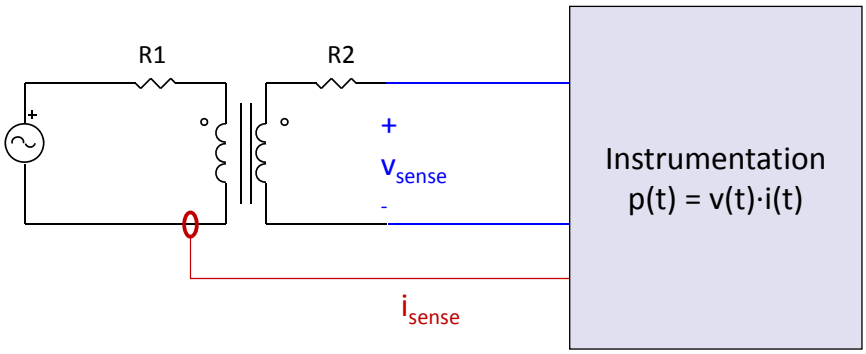
- Calorimetric measurements
  - Can be slow
  - Difficult, but possible, to do accurately
  - Sometimes retain accuracy where electrical measurements lose accuracy
  - Independent check on electrical measurements
- Electrical measurements
  - Conventional four-wire
  - Resonant methods

Calorimetric methods

- Methods:
  - Steady-state temperature rise
  - dT/dt
  - Heat flux sensor: ΔT across a thermal resistor: equivalent of a current sense resistor.
  - Liquid coolant: flow and temperature rise
- Issues:
  - Dissipation in winding is included
  - Isolation: insulation and/or guarding
  - Lead wires

Electrical measurements

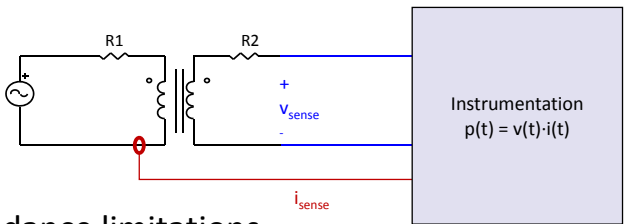
- Conventional two-winding measurement



- Theory:
  - Voltage drop on R1 doesn't appear in measurement.
  - No current, and so no voltage drop, on R2.

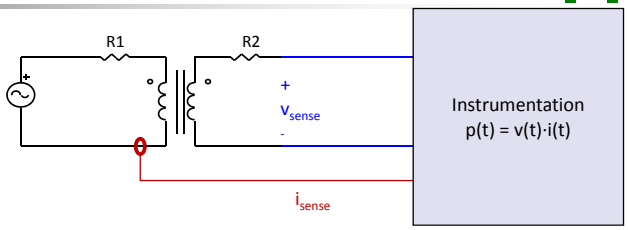
Electrical measurements: Source options

- Sinusoidal oscillator with amplifier.
- Square-wave or other oscillator with amplifier.
  - Rise time and output impedance limitations.



- Power converter, e.g. full bridge.
  - Fast edges.
  - Stiff voltage source.
  - Example: Dartmouth PSMA core loss studies:
    - Programmable pulse generator.
    - Digital control of power supply bus voltage.
    - Automatic sequence of waveforms.

Electrical measurements: Instrumentation options



- Current sensing:
  - Options:
    - Shunt
    - Current transformer
    - Rogowski coil
    - Wideband DC current probe.
  - Critical for any of these: bandwidth and delay (phase shift)
- Power instrumentation: phase shift also critical
  - Power meter
  - Oscilloscope
    - On board power calculation.
    - Data acquisition; loss calculation off line.

Effect of phase error and delay

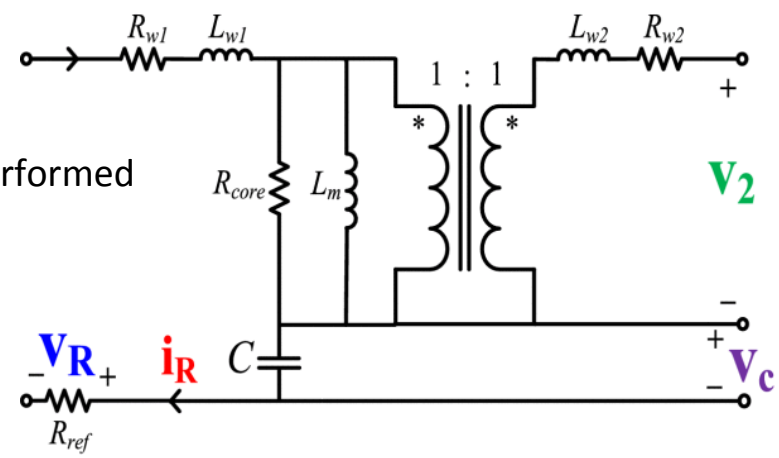
- Fractional error in loss = $Q\,\Delta\varphi$
  where Q is quality factor of the core and Δφ is the phase error in radians.
  - Example: Q = 25, 1° phase error → 44% error!
- Uncompensated delay translates to phase error.
  - 1 ns delay is 0.36° at 1 MHz; 3.6° at 10 MHz;
- Double jeopardy at HF (3~30 MHz frequencies:
  - Small delay becomes intolerable phase shift.
  - Low-permeability materials → high Q.

Resonant methods

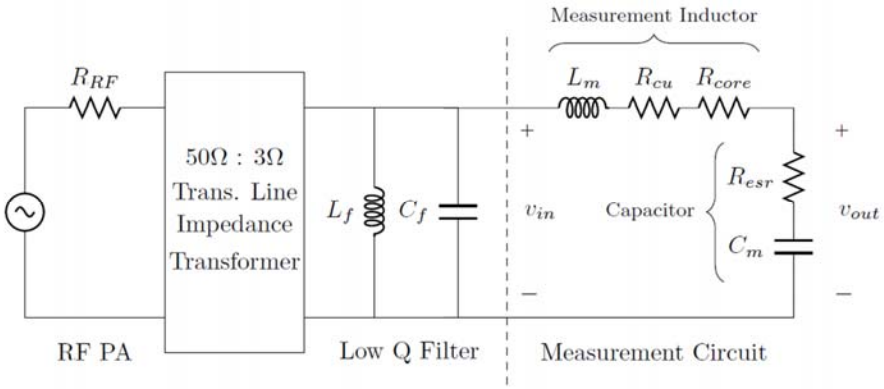
- Virginia Tech resonant-corrected two-winding measurements.
  - Reduces sensitivity to phase errors by cancelling reactive impedance and reducing effective *Q*.
- MIT/Dartmouth direct *Q* measurement.
  - Eliminates sensitivity to phase errors—measure only voltage amplitudes, ignoring phase information.
- Papers provide detailed error analysis for each.

Virginia Tech Resonant Methods

- V_C is used to cancel reactive component of V_2
- This version (T. Pow. Elr. April 2017):
  - Doesn't require tuning cap value.
  - Cancellation performed off line.
  - Inductive version for non-sinusoidal waveforms.



MIT resonant method



- Must be tuned to resonant peak for each measurement frequency.
- Need only amplitudes: Q = |Vout|/|Vin|
- Measurement include winding loss: model it and subtract.

Other issues in electrical measurements

- Winding capacitance
  - Current in winding capacitance is not creating H field.
- Mutual resistance
  - High-frequency winding loss includes mutual resistance terms (discussed in Modelling this afternoon).
  - Mutual resistance appears as part of measured core loss.
  - Windings can be designed for low mutual resistance.
- Temperature control: test temperature + rise during testing.
  - Pulse tests, mineral-oil bath, forced convection.

Types of core loss measurements

- Calorimetric measurements
- Electrical measurements
  - Conventional four-wire
    - Instrumentation options
    - Source options
  - Resonant methods
    - MIT
    - Virginia Tech

References

For additional references see reference lists in each of these.

D. Hou, M. Mu, F. C. Lee and Q. Li, "New High-Frequency Core Loss Measurement Method With Partial Cancellation Concept," in *IEEE Transactions on Power Electronics*, vol. 32, no. 4, pp. 2987-2994, April 2017. doi: 10.1109/TPEL.2016.2573273

Y. Han, G. Cheung, A. Li, C. R. Sullivan and D. J. Perreault, "Evaluation of Magnetic Materials for Very High Frequency Power Applications," in *IEEE Transactions on Power Electronics*, vol. 27, no. 1, pp. 425-435, Jan. 2012. doi: 10.1109/TPEL.2011.2159995

C.R. Sullivan, J.H. Harris, Testing Core Loss for Rectangular Waveforms, Phase II Final Report, 2011, Thayer School of Engineering at Dartmouth, http://www.psma.com/coreloss/phase2.pdf

A. van den Bossche and V. Valchev, *Inductors and Transformers for Power Electronics*. Taylor and Francis, 2005.