Survey of Core Loss Test Methods

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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: $\Delta T$ 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.

\[ p(t) = v(t) \cdot i(t) \]
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.

$p(t) = v(t) \cdot i(t)$
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 = $Q \Delta \phi$
  where $Q$ is quality factor of the core and $\Delta \phi$ is the phase error in radians.
  - Example: $Q = 25$, $1^\circ$ phase error $\rightarrow$ 44% error!
- Uncompensated delay translates to phase error.
  - 1 ns delay is $0.36^\circ$ at 1 MHz; $3.6^\circ$ at 10 MHz;
- Double jeopardy at HF (3~30 MHz frequencies:
  - Small delay becomes intolerable phase shift.
  - Low-permeability materials $\rightarrow$ 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: \( Q = \frac{|V_{\text{out}}|}{|V_{\text{in}}|} \)
- 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.

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doi: 10.1109/TPEL.2011.2159995


*Paper at APEC 2017 on winding resistance measurement:*