Small Signal Measurement Techniques for Magnetic Components

Dr. Jenna Pollock

PSMA: Power Magnetics @ High Frequency Workshop 2019
Component Characterization

• Small signal measurements
  • R, L, C

• Analytical method to calculate impedances
  • Magnetizing inductance
    • Al value
    • Reluctance with core permeability
  • Leakage inductance
    • Pot core configuration

• Resistances
  • Dc resistance
  • Ac resistance
    • Fr
    • 1D field approximation

• Could use numerical methods
Two Winding Transformer Circuit Model

\[ R_p \quad L_{\text{leakage,all}} \quad 1:n \quad R_s \]

\[ C_{w,p} \quad L_m \quad R_{\text{core}} \]

\[ C_{\text{interwinding}} \quad C_{w,s} \]
Inductor Circuit Models

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5.2 Inductor measurement

5.2.1 Paracitics of an inductor

An inductor consists of wire wound around a core and is characterized by the core material used. Air is the simplest core material for making inductors, but for volumetric efficiency of the inductor, magnetic materials such as iron, permalloy, and ferrites are commonly used. A typical equivalent circuit for an inductor is shown in Figure 5-9 (a). In this figure, $R_p$ represents the magnetic loss (which is called iron loss) of the inductor core, and $R_s$ represents the copper loss (resistance) of the wire. $C$ is the distributed capacitance between the turns of wire. For small inductors the equivalent circuit shown in Figure 5-9 (b) can be used. This is because the value of $L$ is small and the stray capacitance between the lead wires (or between the electrodes) becomes a significant factor.

Figure 5-9. Inductor equivalent circuit


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5.3 Transformer measurement

A transformer is one end-product of an inductor so, the measurement techniques are the same as those used for inductor measurement. Figure 5-18 shows a schematic with the key measurement parameters of a transformer. This section describes how to measure these parameters, including \( L, C, R, \) and \( M \).

![Transformer schematic](image)

**Figure 5-18. Transformer parameters**

- \( L_1 \): Primary inductance
- \( L_2 \): Secondary inductance
- \( C_1, C_2 \): Distributed capacitance of windings
- \( R_1, R_2 \): DC resistance of windings
- \( C \): Inter-winding capacitance
- \( M \): Mutual inductance
5.3.1 Primary inductance (L1) and secondary inductance (L2)

L1 and L2 can be measured directly by connecting the instrument as shown in Figure 5-19. All other windings should be left open. Note that the inductance measurement result includes the effects of capacitance. If the equivalent circuit analysis function of Keysight’s impedance analyzer is used, the individual values for inductance, resistance, and capacitance can be obtained.

Leakage inductance is a self-inductance due to imperfect coupling of the transformer windings and resultant creation of leakage flux. Obtain leakage inductance by shorting the secondary with the lowest possible impedance and measuring the inductance of the primary as shown in Figure 5-20.
Transformer Measurements

5.3.2 Inter-winding capacitance (C)

The inter-winding capacitance between the primary and the secondary is measured by connecting one side of each winding to the instrument as shown in Figure 5-21.

5.3.3 Mutual inductance (M)

Mutual inductance (M) can be obtained by using either of two measurement methods:

(1) The mutual inductance can be derived from the measured inductance in the series aiding and the series opposing configurations (see Figure 5-22 (a).) Since the combined inductance (La) in the series aiding connection is La = L1 + L2 + 2M and that Lo in the series opposing connection is Lo = L1 + L2 - 2M, the mutual inductance is calculated as M = (La - Lo)/4.

(2) By connecting the transformer windings as shown in Figure 5-22 (b), the mutual inductance value is directly obtained from inductance measurement. When test current (I) flows through the primary winding, the secondary voltage is given by V = jωM x I. Therefore, the mutual inductance can be calculated from the ratio between the secondary voltage (V) and the primary current (I). However, the applicable frequency range of both measurement techniques is limited by the type and the parameter values of the transformer being measured. These methods assume that the stray capacitance effect, including the distributed capacitance of windings, inter-winding capacitance, and test lead capacitance, is sufficiently small. To minimize the cable capacitance effect for the method shown in Figure 5-22 (b), the Hp test lead length should be made as short as possible. It is recommend to use both techniques and to cross-check the results.
Transformer Measurements

Figure 5-21. Inter-winding capacitance measurement

Figure 5-22. Mutual inductance measurement

(a) Series aiding and series opposing

(b) Direct connection technique

\[
L_a = L_1 + L_2 + 2M \\
L_o = L_1 + L_2 - 2M
\]

\[
M = \frac{L_a - L_o}{4}
\]

\[
V = j\omega M \\
M = \frac{V}{j\omega}
\]
Test Fixture 16047E

Up to 120 MHz (4-Terminal Pair): Lead Components continued

16047E Test fixture

Terminal connector: 4-Terminal Pair, BNC
DUT connection: 2-Terminal
Dimensions (approx.):
135 (W) x 40 (H) x 65 (D) [mm]
Weight (approx.): 200 g
Additional error:

<table>
<thead>
<tr>
<th>Type of error</th>
<th>Impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional error</td>
<td>$0.2 \times (f/100)^{2} %$</td>
</tr>
<tr>
<td>$f \leq 15 \text{ MHz}$</td>
<td></td>
</tr>
<tr>
<td>Proportional error</td>
<td>$4 \times (f/100) %$</td>
</tr>
<tr>
<td>$f &gt; 15 \text{ MHz}$</td>
<td></td>
</tr>
<tr>
<td>Open repeatability</td>
<td>$2 + 10 \mu \times (f/100)$ [S]</td>
</tr>
<tr>
<td>Short repeatability</td>
<td>$2 \pm 600 , m \times (f/100)$ [Ω]</td>
</tr>
</tbody>
</table>

Description: This test fixture is designed for impedance evaluation of lead type devices up to 120 MHz. A guard terminal is available for three terminal devices and a shorting plate comes secured on this fixture.


Frequency: DC to 120 MHz

Maximum voltage: ±42 V peak max. (AC+DC)

Operating temperature: −20 to 75°C

DUT: See figure below with 16047E’s electrode size.

Furnished accessories:
Test Fixture 16047E

• Calibration

**Compensation and measurement:** Open and short compensations are recommended before measurement. Short compensation is performed by shorting the contacts of the test fixture with a shorting plate. After performing open and short compensations, the DUT is connected to the test fixture. The following figures show how compensation and measurement are performed.
Accuracy

• Keysight
  • E4990A
Predicting Inductance Roll-off with DC Excitation

Fig. 2. The test setup used to measure inductance with large dc bias currents.

![Diagram of test setup](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prototype 1</th>
<th>Prototype 2</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Size</td>
<td>EI225</td>
<td>E54/24/19</td>
<td>NA</td>
</tr>
<tr>
<td>Effective core area, $A_{core}$</td>
<td>3.58x10^{-4}</td>
<td>3.7x10^{-4}</td>
<td>m²</td>
</tr>
<tr>
<td>Effective core length, $l_{core}$</td>
<td>115</td>
<td>107</td>
<td>mm</td>
</tr>
<tr>
<td>Number of turns, $N$</td>
<td>30</td>
<td>30</td>
<td>NA</td>
</tr>
<tr>
<td>Winding Type</td>
<td>Foil</td>
<td>Wire</td>
<td>NA</td>
</tr>
</tbody>
</table>

Fig. 5. Measured inductance roll-off compared to predicted behavior for 60 permeability Kool Mu powdered sendust material in prototype #2.

![Graph of measured vs predicted inductance roll-off](image)

Fig. 6. Measured inductance roll-off compared to predicted behavior for 3C90 ferrite material in prototype #2. The predictions are based on material properties from the manufacturer’s datasheet. A better match was obtained when we made our own measurements, as will be shown in Fig. 8.

![Graph of measured vs predicted inductance roll-off](image)
Extracting Winding Resistance

A Step-by-Step Guide to Extracting Winding Resistance from an Impedance Measurement

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Thayer School of Engineering
Dartmouth College
Hanover, NH 03755 USA
Email: {Benedict.Foo.th, Aaron.L.Stein, Charles.R.Sullivan}@dartmouth.edu

Fig. 2. Circuit model representing winding impedance for measurement interpretation.

Fig. 3. Block diagram of small signal core resistance measurement.

Fig. 5. Three winding connections to be measured for resistance matrix.

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Impedance-Analyzer Measurements

Impedance-Analyzer Measurements of High-Frequency Power Passives: Techniques for High Power and Low Impedance

Satish Prabhakaran  Charles R. Sullivan
Thayer School of Engineering, Dartmouth College
http://engineering.dartmouth.edu/inductor/
Satish@dartmouth.edu  Charles.R.Sullivan@dartmouth.edu

Fig. 6. Layout of the test fixture designed for low stray impedance.

Fig. 1. Schematic of the Auto Balancing Bridge Measurement [6]
Example Inductor using ShapeOpt

Prototype:
PQ4040 PC95
20 turns
650 x 44 AWG
All legs gapped to 2 mm

ShapeOpt Inductor Parameters

Enter inductor parameters for your system. Click on each field text for further explanation. Click on the "Go!" button at the bottom of the page to calculate loss predictions and generate optimal designs.

Choose a standard core size or select "user defined" to specify a different size:

- Breadth of the core window (mm): 29.5 mm
- Height of the core window (mm): 11.05 mm
- Breadth of the bobbin window (mm): 25.4 mm
- Height of the bobbin window (mm): 9.76 mm
- Gap length (mm): 2 mm
- Centerpost Diameter (mm): 17.8 mm

Core gaps:

- Center leg gapped
- Outer legs gapped

All legs gapped
- round centerpost
- square centerpost

• http://power.thayer.dartmouth.edu/shapeopt_spec.html
**ShapeOpt: Data Entry**

- Frequency = 300 kHz
- Peak current = 10 A

<table>
<thead>
<tr>
<th>Current Sinusoidal Waveform Data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency:</strong> 300000 Hz</td>
</tr>
<tr>
<td><strong>Amplitude:</strong> 10 A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Winding Information</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operating temperature (used to calculate copper resistivity):</strong> 20°C</td>
</tr>
<tr>
<td><strong>Wire Packing factor:</strong> 0.25</td>
</tr>
<tr>
<td><strong>Number of turns:</strong> 20</td>
</tr>
<tr>
<td><strong>Wire gauge:</strong> 0.044 mm awg</td>
</tr>
<tr>
<td><strong>Wire insulation type:</strong> Single Build</td>
</tr>
</tbody>
</table>

**Alternate Modes**

- Default Optimization
- Force Full Bobbin
- Force Fixed Number of Strands

**Optional field calculation parameters**

<table>
<thead>
<tr>
<th>Horizontal divisions in the winding:</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical divisions in the winding:</td>
<td>20</td>
</tr>
<tr>
<td>Divisions in the gap:</td>
<td>10</td>
</tr>
<tr>
<td>Number of images of the Winding Window Geometry to be computed in the x-direction:</td>
<td>5</td>
</tr>
<tr>
<td>Number of images of the Winding Window Geometry to be computed in the y-direction:</td>
<td>5</td>
</tr>
</tbody>
</table>
ShapeOpt: Outputs

Optimal Winding Shape
ShapeOpt: Outputs

**Note:**
- Samples built with 650 strands and ShapeOpt calls for 682
  - That’s a pretty good match
  - Could use “Force fixed number of strands” mode
- Many more parameters to vary
- Play with the tool at:
  - [http://power.thayer.dartmouth.edu/shapeopt_spec.html](http://power.thayer.dartmouth.edu/shapeopt_spec.html)

<table>
<thead>
<tr>
<th>Optimal Winding Information</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of strands</td>
<td>682</td>
</tr>
<tr>
<td>[\int B^2 - dS \text{ over winding area} ]</td>
<td>1.37448e-08 T²m²</td>
</tr>
<tr>
<td>Average turn length</td>
<td>0.0910117 m</td>
</tr>
</tbody>
</table>

**Power Loss**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AC loss</td>
<td>1.70768 W</td>
</tr>
<tr>
<td>DC loss</td>
<td>2.3628 W</td>
</tr>
<tr>
<td>Total loss</td>
<td>4.07048 W</td>
</tr>
</tbody>
</table>

Prototype:
PQ4040 PC95
20 turns
650 x 44 AWG
All legs gapped to 2 mm
Measured Inductor Resistance

Full bobbin rectangular winding vs. Shaped winding

PQ4040 PC95
20 turns
650 x 44 AWG
All legs gapped to 2 mm

Shaped winding reduces measured resistance

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Inductor Builds

- **Shaped Winding Layout**
- **Rectangular Winding Layout**

| PQ4040 PC95 | 20 turns | 650 x 44 AWG | All legs gapped to 2 mm |

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Inductor Build: Winding Layouts

Rectangular Winding Layout

Shaped Winding Layout

Build samples:

Rectangular Winding Layout

Shaped Winding Layout

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Special Thanks to:

• Keysight Technologies
• Ed Herbert, PSMA
• Duanyang Wang, SF Motors
References:

• Keysight Technologies, www.keysight.com
• S. Prabhakaran, C. R. Sullivan, “Impedance-Analyzer Measurements of High-Frequency, High Power Passives,