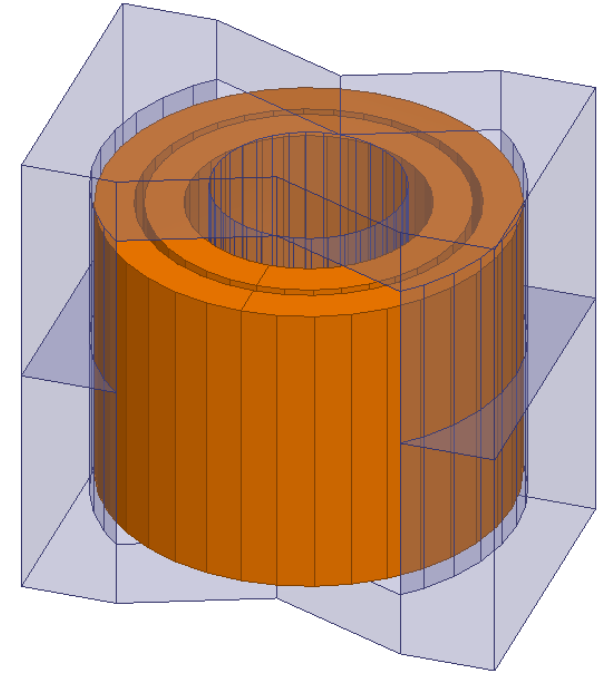


Small Signal Measurement Techniques for Magnetic Components

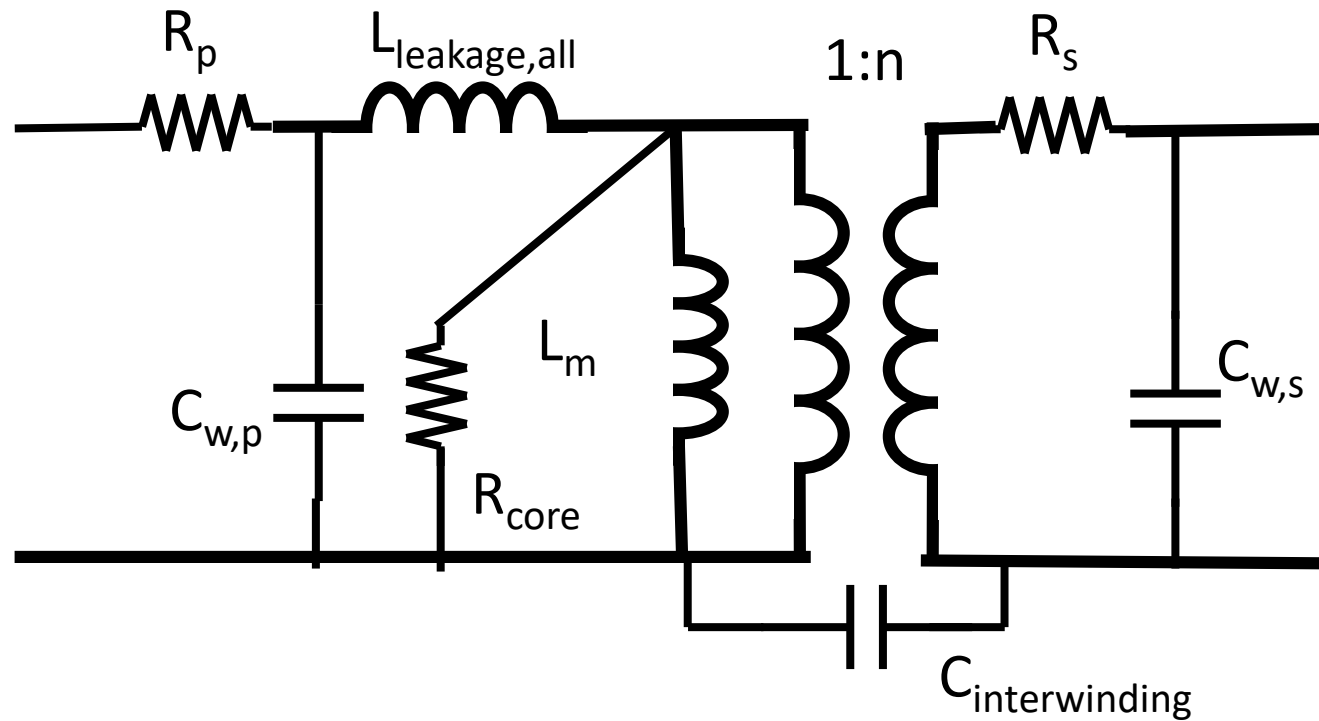
Dr. Jenna Pollock

Component Characterization

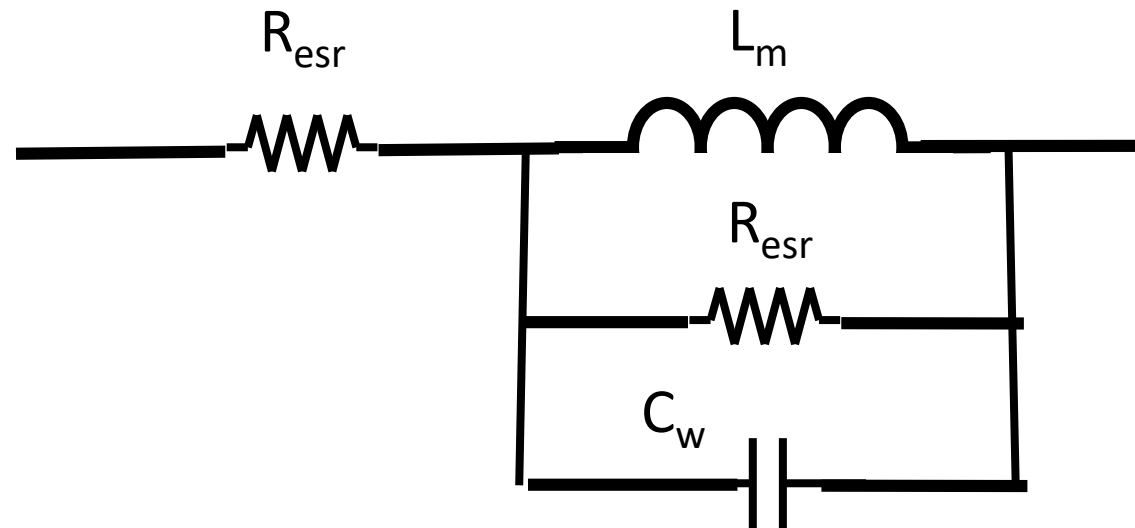
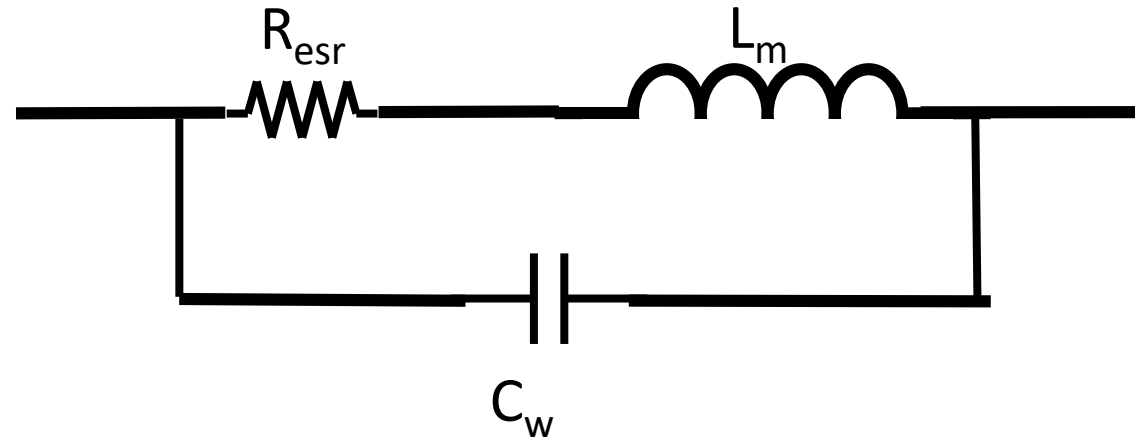
- Small signal measurements
 - R, L, C
- Analytical method to calculate impedances
 - Magnetizing inductance
 - Al value
 - Reluctance with core permeability
 - Leakage inductance
 - Pot core configuration
 - Resistances
 - Dc resistance
 - Ac resistance
 - Fr
 - 1D field approximation
- Could use numerical methods



Two Winding Transformer Circuit Model



Inductor Circuit Models



Inductor Measurement

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.

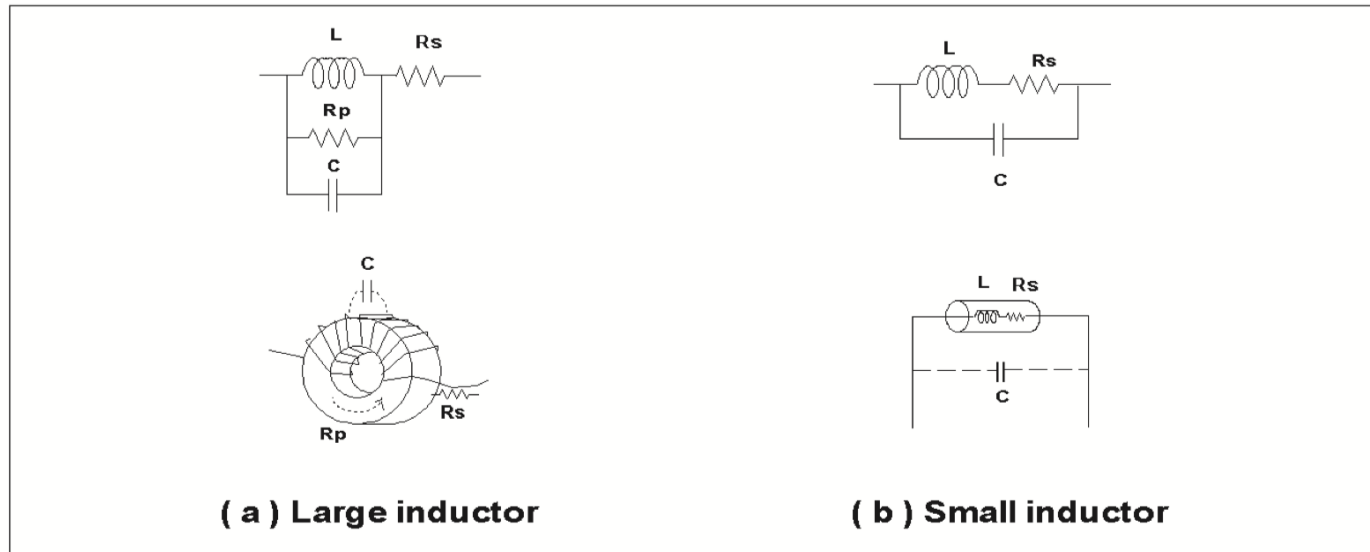


Figure 5-9. Inductor equivalent circuit

Transformer Measurements

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.

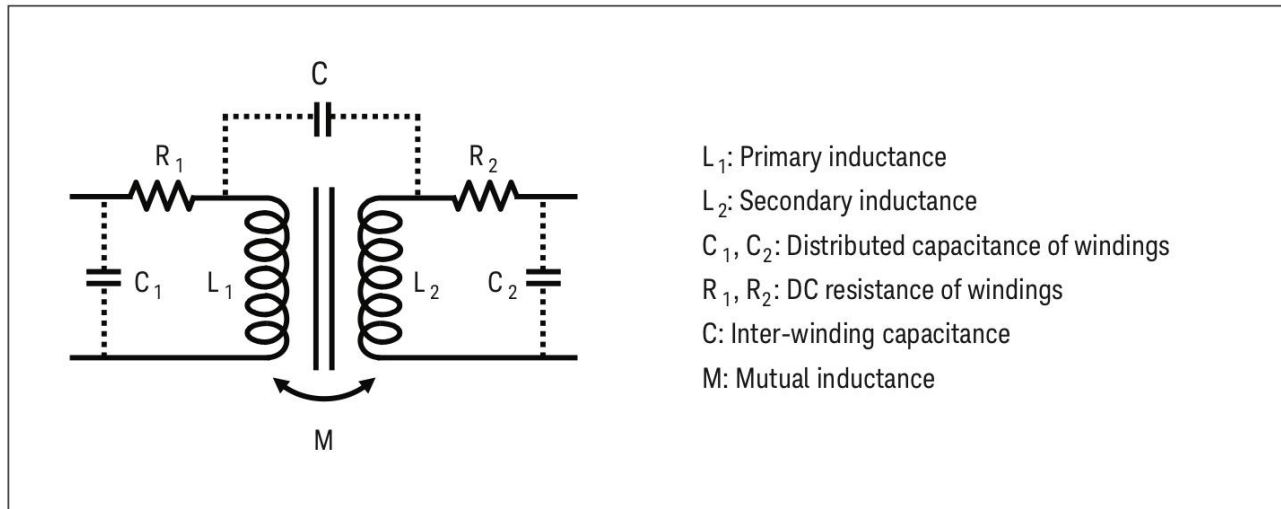


Figure 5-18. Transformer parameters

Transformer Measurements

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.

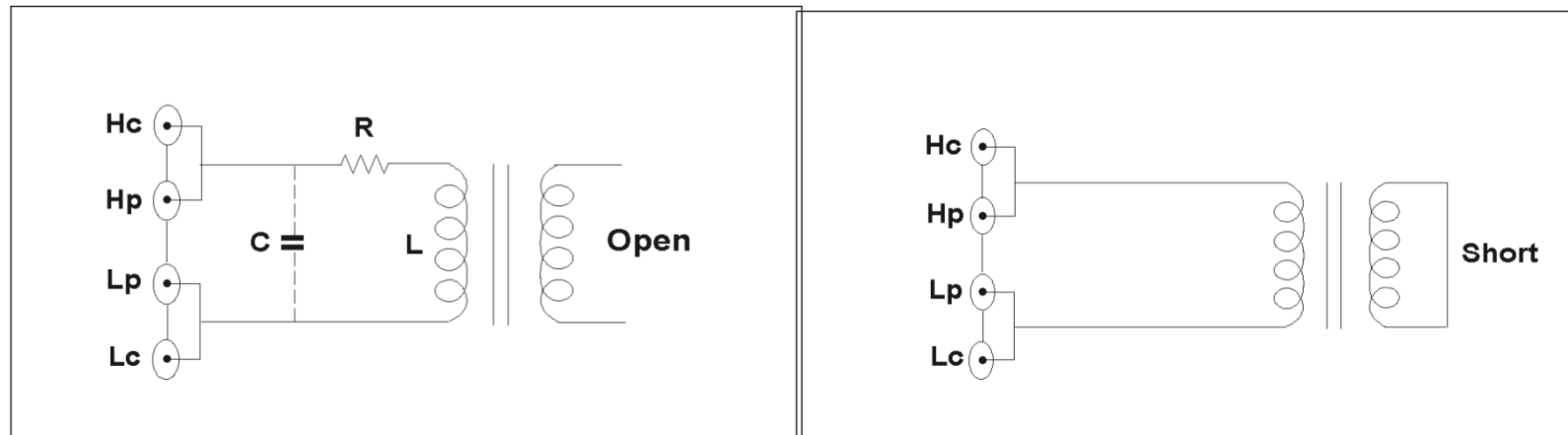


Figure 5-19. Primary inductance measurement

Figure 5-20. Leakage inductance measurement

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 (L_a) in the series aiding connection is $L_a = L_1 + L_2 + 2M$ and that L_o in the series opposing connection is $L_o = L_1 + L_2 - 2M$, the mutual inductance is calculated as $M = (L_a - L_o)/4$.

(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 $V = j\omega M \times I$. 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

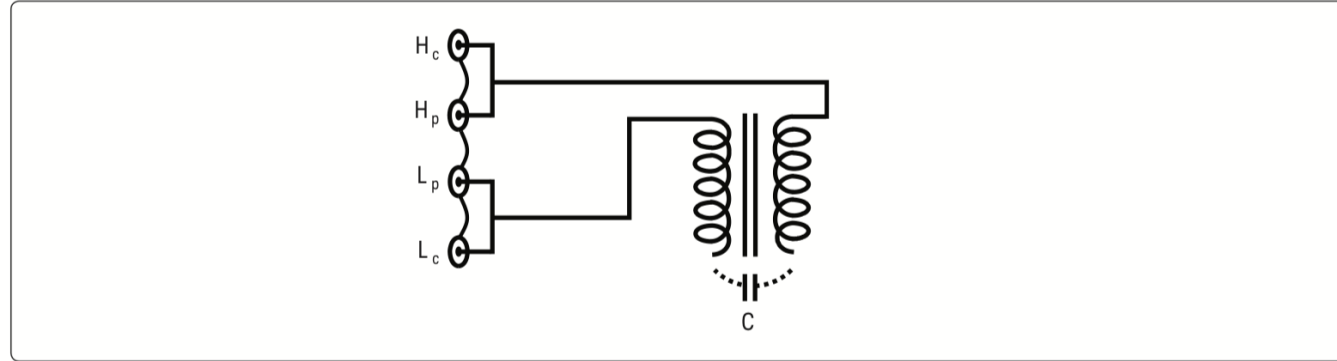


Figure 5-21. Inter-winding capacitance measurement

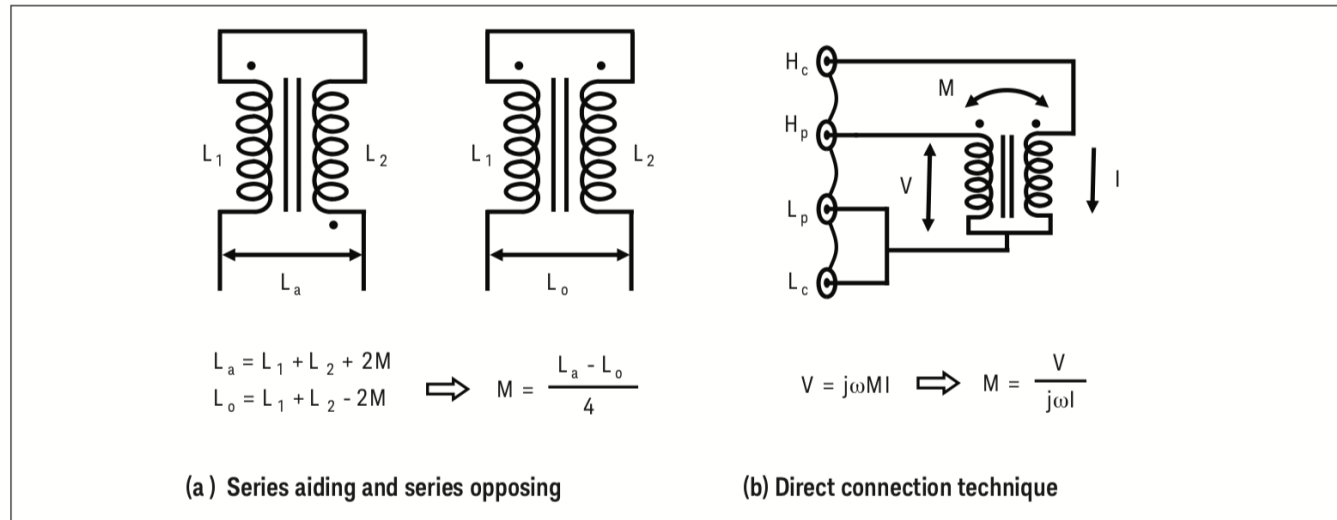


Figure 5-22. Mutual inductance measurement

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:

Type of error	Impedance
Proportional error $f \leq 15$ MHz	$0.2 \times (f/100)^2$ [%]
Proportional error $f > 15$ MHz	$4 \times (f/100)$ [%]
Open repeatability	$2 n + 10 \mu \times (f/100)$ [S]
Short repeatability	$2 m + 600 m \times (f/100)$ [Ω]

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.

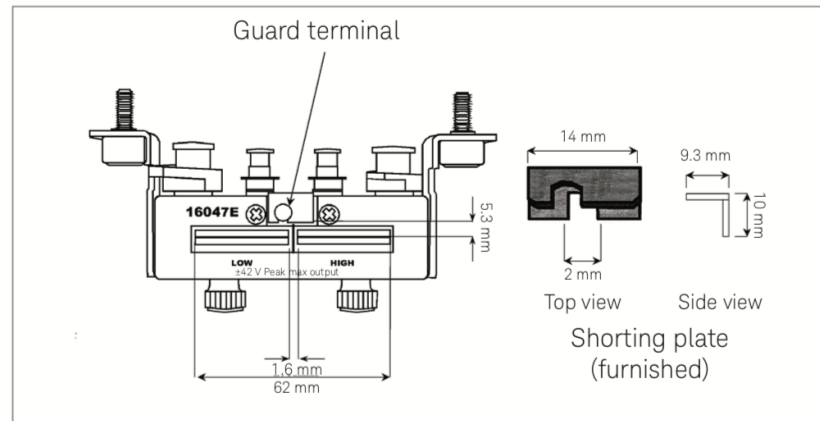
Applicable instruments: E4980A/AL, E4981A, E4990A, E5061B-3L3/3L4/3L5 with Opt. 005

Frequency: DC to 120 MHz

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

Operating temperature: -20 to 75°C

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

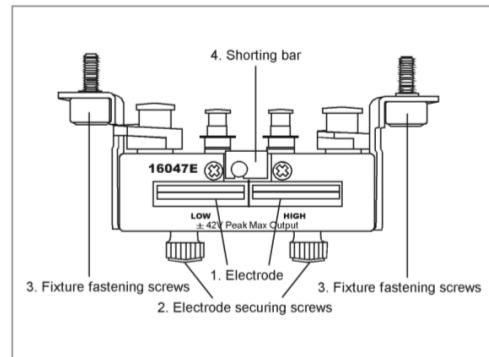


Furnished accessories:

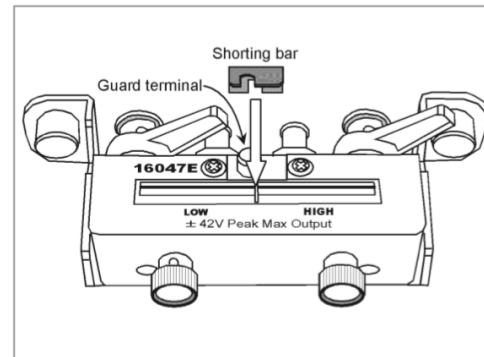
Test Fixture 16047E

- Calibration

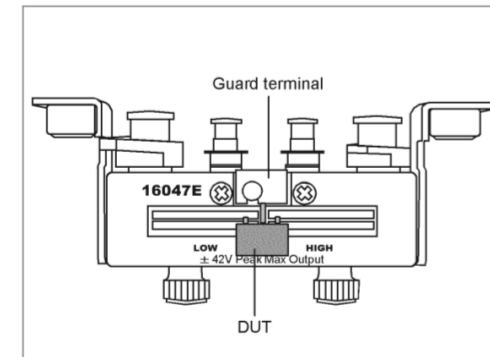
Compensation and measurement: Open and short compensations are recommended before measurement. Short compensation is performed by shorting the contacts of the test fixture with a shorting plate. After performing open and short compensations, the DUT is connected to the test fixture. The following figures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



Test fixture overview



Connecting a shorting plate



Measuring 3-Terminal device

Accuracy

- Keysight
 - E4990A

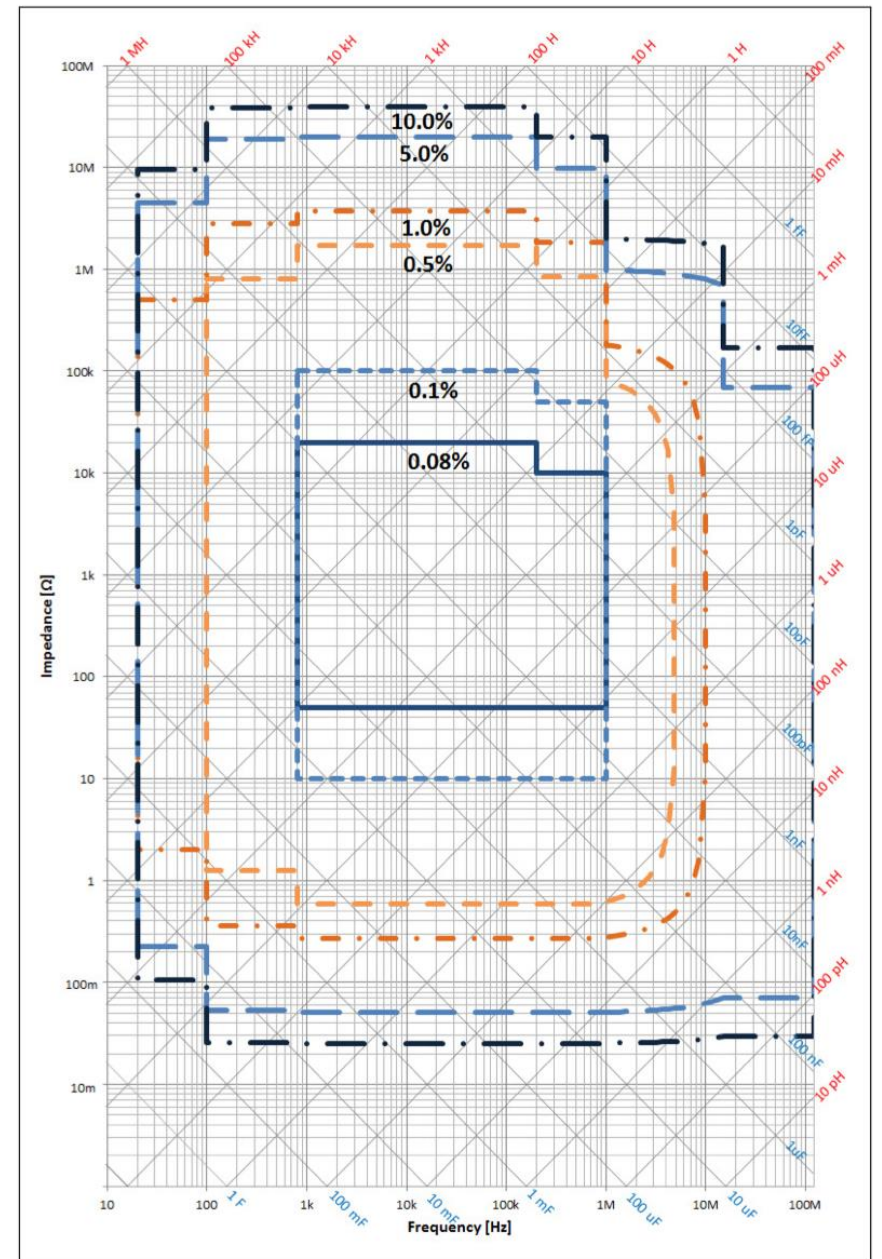


Figure 5. Impedance measurement accuracy at four-terminal pair port of the E4990A's front panel (Oscillator level = 0.5 Vrms), measurement time = 5 (Typical at > 10 MHz)

Predicting Inductance Roll-off with DC Excitation

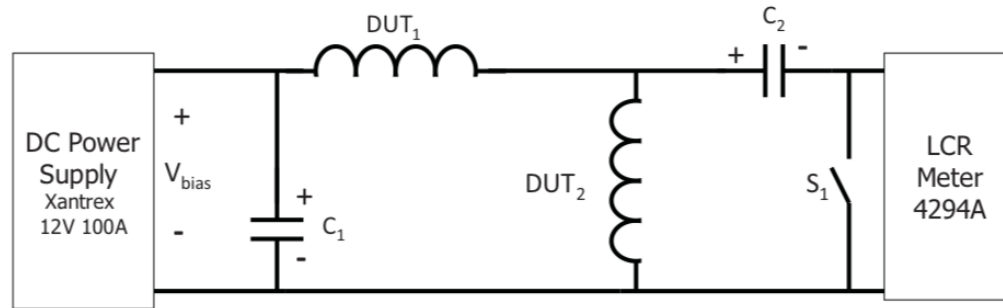


Fig. 2. The test setup used to measure inductance with large dc bias currents.

TABLE II
INDUCTOR SPECIFICATIONS

Parameter	Prototype 1	Prototype 2	Units
Core Size	EI225	E54/24/19	NA
Effective core area, A_{core}	3.58×10^{-4}	3.37×10^{-4}	m^2
Effective core length, ℓ_{core}	115	107	mm
Number of turns, N	30	30	NA
Winding Type	Foil	Wire	NA

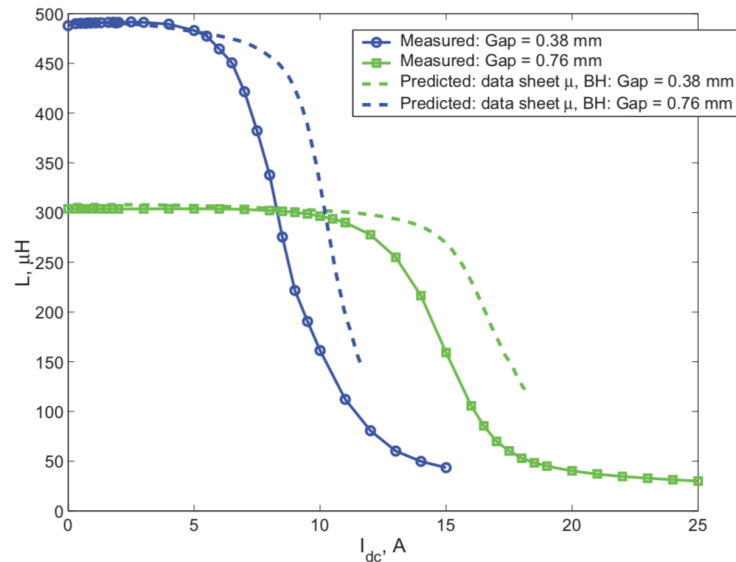


Fig. 6. Measured inductance roll-off compared to predicted behavior for 3C90 ferrite material in prototype #2. The predictions are based on material properties from the manufacturer's datasheet. A better match was obtained when we made our own measurements, as will be shown in Fig. 8.

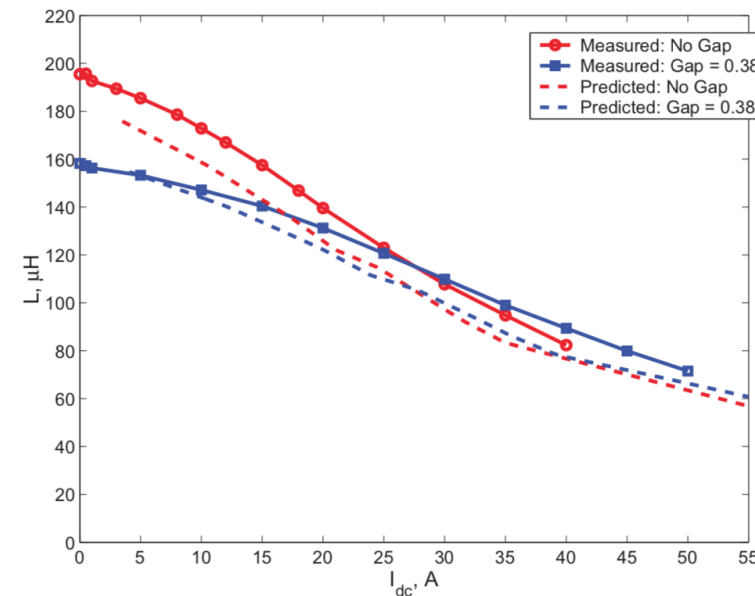


Fig. 5. Measured inductance roll-off compared to predicted behavior for 60 permeability Kool Mu powdered sendust material in prototype #2.

Extracting Winding Resistance

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

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

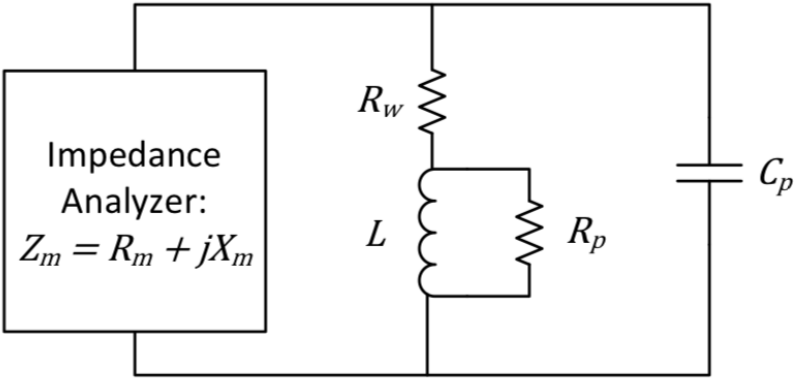


Fig. 2. Circuit model representing winding impedance for measurement interpretation.

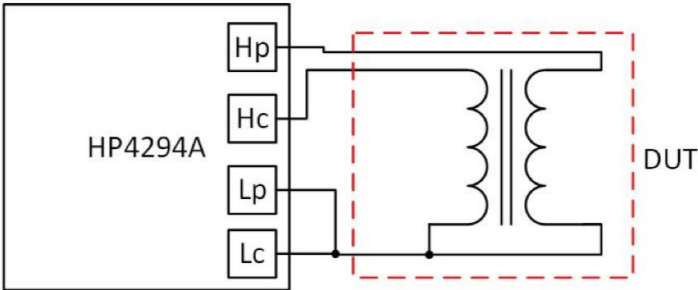


Fig. 3. Block diagram of small signal core resistance measurement.

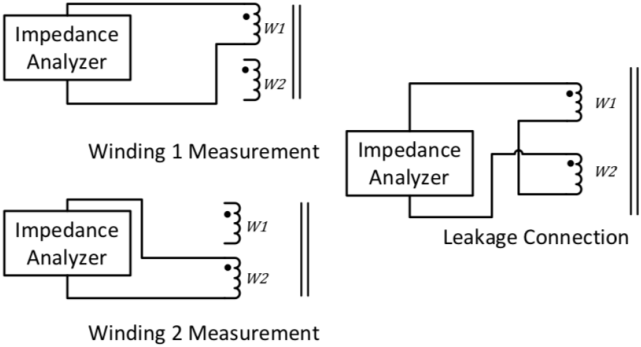


Fig. 5. Three winding connections to be measured for resistance matrix.

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

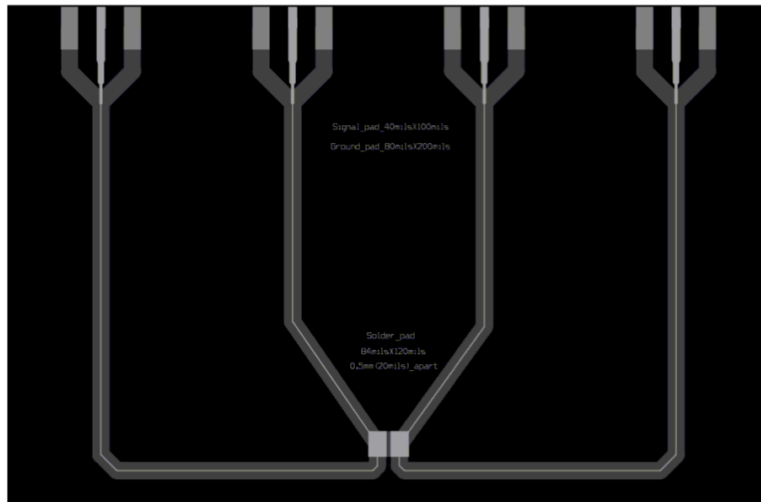


Fig. 6. Layout of the test fixture designed for low stray impedance.

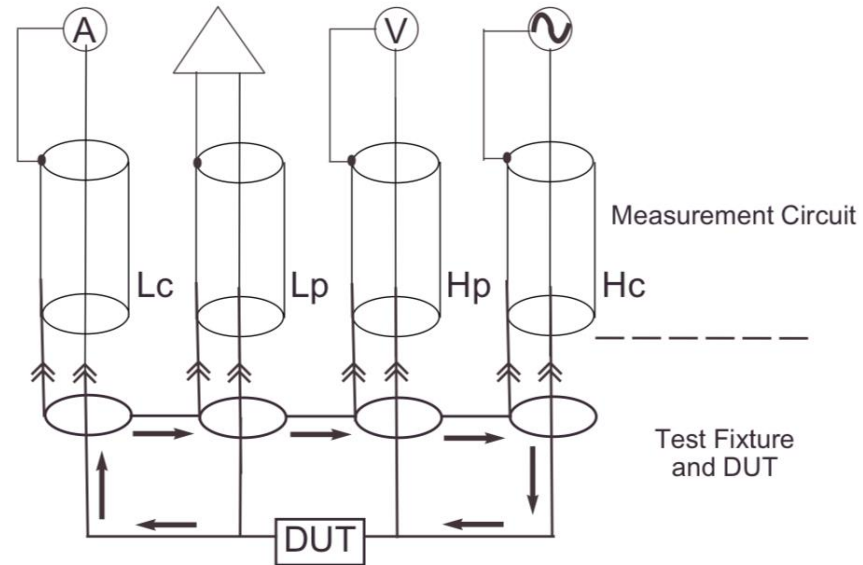
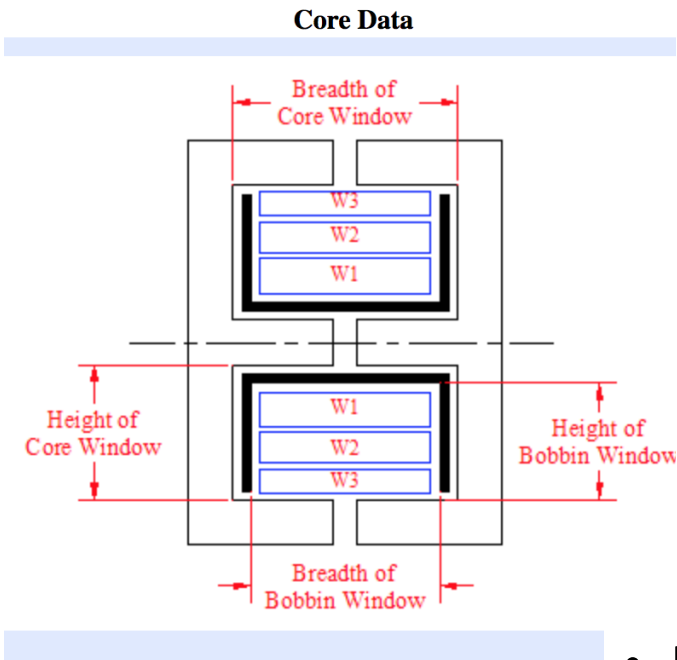


Fig. 1. Schematic of the Auto Balancing Bridge Measurement [6]

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:	PQ40/40	
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):	9.75	mm
Gap length (mm):	2	mm
Centerpost Diameter (mm):	17.5	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

Current Sinusoidal Waveform Data		
Frequency:	<input type="text" value="300000"/>	Hz
Amplitude:	<input type="text" value="10"/>	A

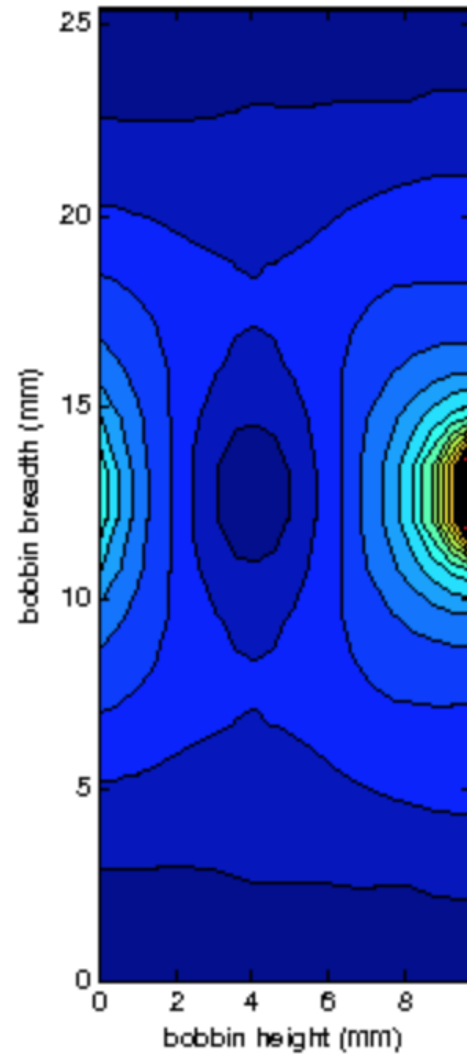
Winding Information		
Operating temperature (used to calculate copper resistivity):	<input type="text" value="20"/>	C
Wire Packing factor:	<input type="text" value="0.25"/>	
Number of turns:	<input type="text" value="20"/>	
Wire gauge:	<input type="text" value="44"/>	awg
Wire insulation type:	<input checked="" type="radio"/> Single Build <input type="radio"/> Heavy Build	
<input type="checkbox"/> Override wire diameter:		mm

Alternate Modes	
<input checked="" type="radio"/>	Default Optimization
<input type="radio"/>	Force Full Bobbin
<input type="radio"/>	Force Fixed Number of Strands

Optional field calculation parameters	
Horizontal divisions in the winding:	<input type="text" value="20"/>
Vertical divisions in the winding:	<input type="text" value="20"/>
Divisions in the gap:	<input type="text" value="10"/>
Number of images of the Winding Window Geometry to be computed in the x-direction:	<input type="text" value="5"/>
Number of images of the Winding Window Geometry to be computed in the y-direction:	<input type="text" value="5"/>

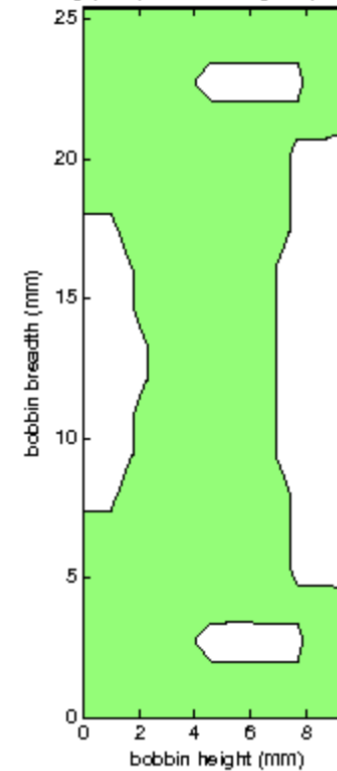
ShapeOpt: Outputs

Magnitude of B – gap at (0, bw/2), plane parallel to core



Optimal Winding Shape

Optimal shape of the winding (wire placement in green) – gap is at coordinates (0, 12.7)



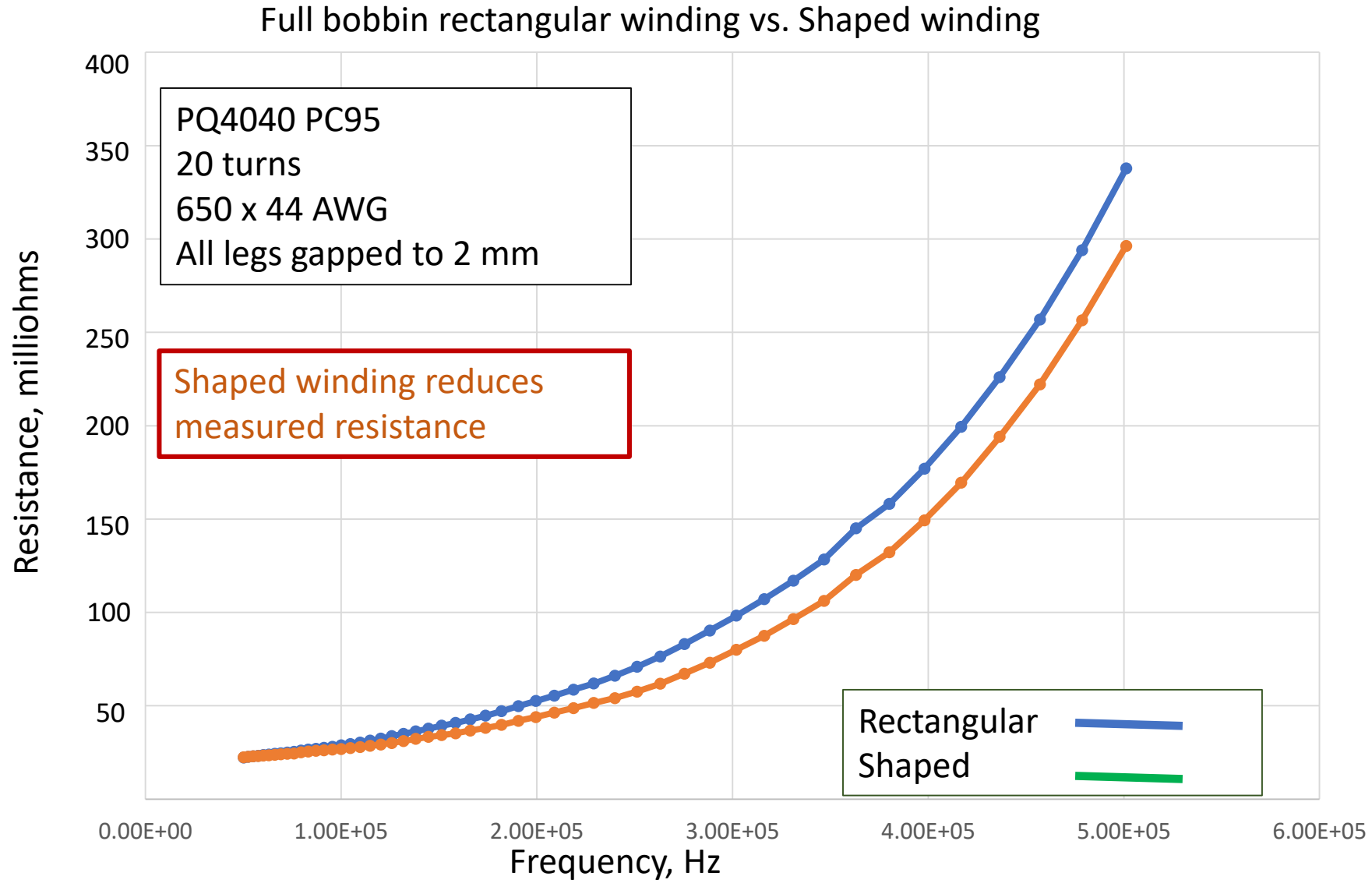
ShapeOpt: Outputs

Optimal Winding Information	
Number of strands	682
$\iint B^2 \cdot dS$ over winding area	1.37448e-08 T ² ·m ²
Average turn length	0.0910117 m
Power Loss	
AC loss	1.70768 W
DC loss	2.3628 W
Total loss	4.07048 W

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

- 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

Measured Inductor Resistance

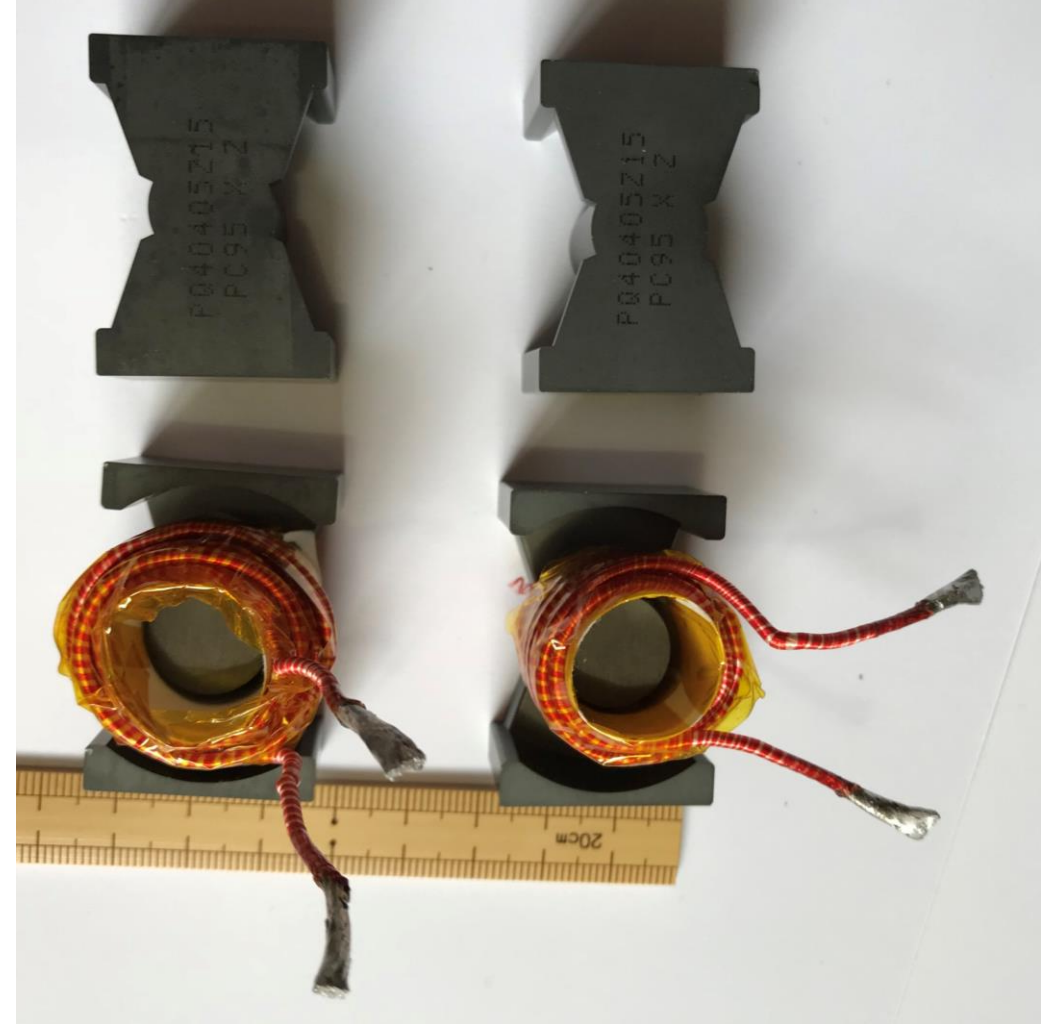


Inductor Builds

Shaped Winding Layout

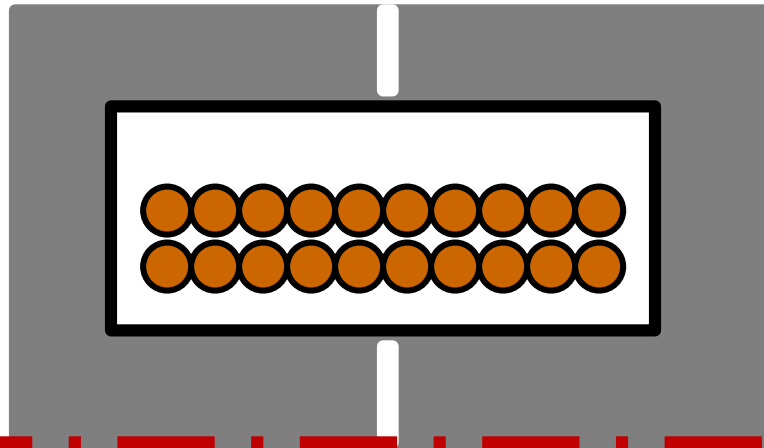
Rectangular Winding Layout

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

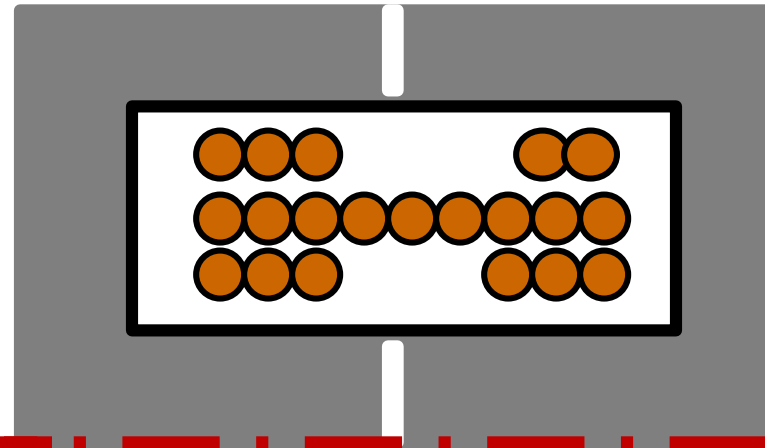


Inductor Build: Winding Layouts

Rectangular Winding Layout

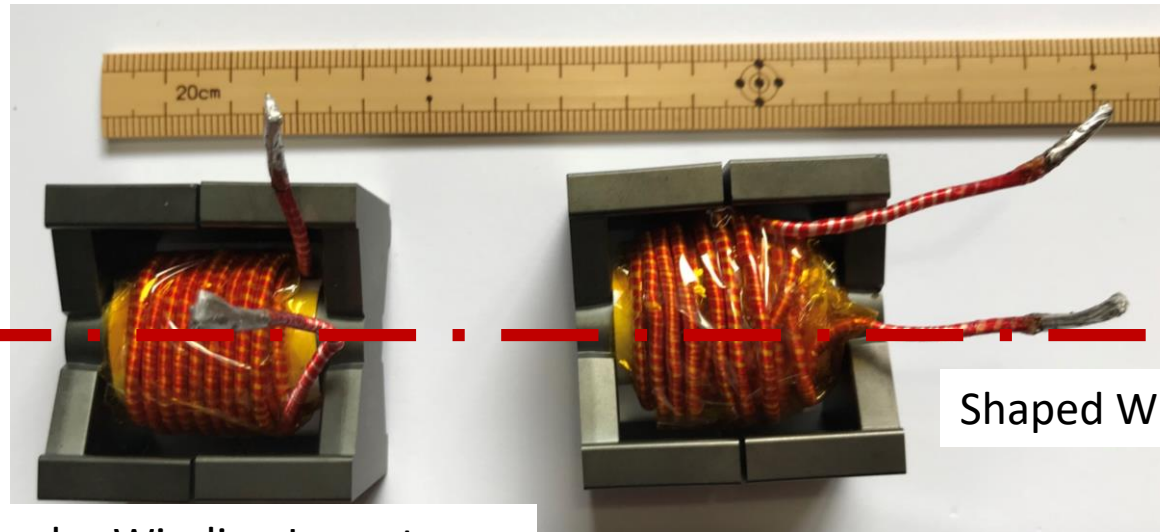


Shaped Winding Layout



centerline

Build samples:



centerline

Shaped Winding Layout

Rectangular Winding Layout

Special Thanks to:

- Keysight Technologies
- Ed Herbert, PSMA
- Duanyang Wang, SF Motors

References:

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- Dartmouth Magnetic Component Research Web Site, <http://engineering.dartmouth.edu/inductor>.
- C. R. Sullivan and R. Zhang;, “Simplified design method for litz wire,” in IEEE 29th Annual Applied Power Electronics Conference, 2014, pp. 2667–2674.
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- B. X. Foo, A. L.F Stein, C.R. Sullivan, A” Step-by-Step Guide to Winding Resistance Extraction from an Impedance Measurements,” IEEE APEC 2017.
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- S. Prabhakaran, C. R. Sullivan, “Impedance-Analyzer Measurements of High-Frequency, High Power Passives,