Challenges of Magnetic Component Core and Copper Loss Measurement

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Isolation of core and winding loss in a transformer or inductor can prove a challenging task.

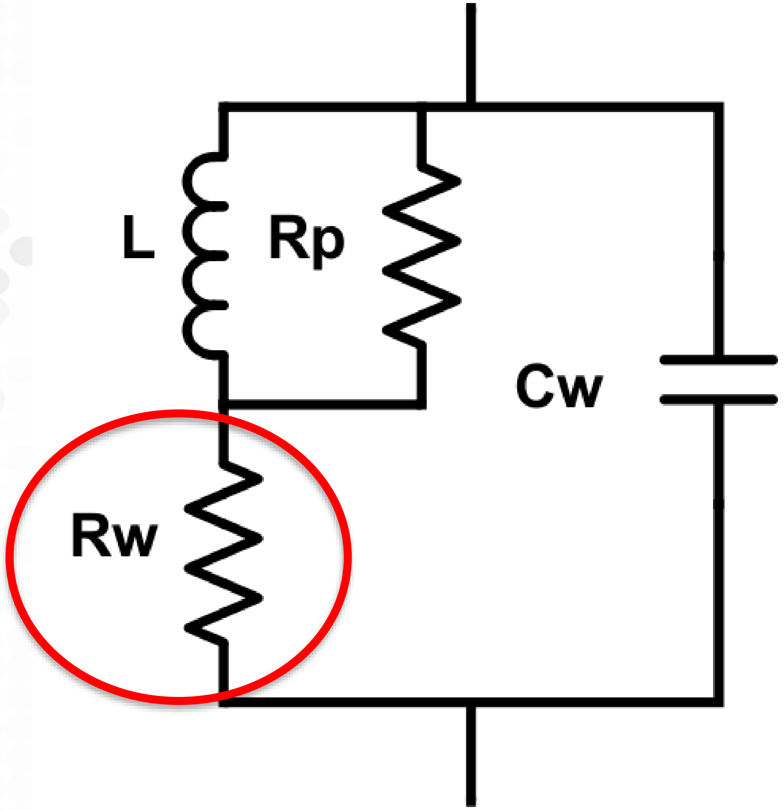
Device must be evaluated prior to test to establish if extraction is useful

Simulation might be more accurate and faster choice

Results must be interpreted carefully

Measurement error can provide incorrect results that may or may not be easily caught

Goals using an impedance analyzer



Model magnetic device per the schematic at left.

From impedance analyzer gain 2 measurements – R_m, X_m .(real and imaginary impedance, can be extracted from Z and phase angle)

Require two more measurements to solve system and extract Rw.

Need to find Cw and Rp.

Find Cw using DUT's self-resonant frequency

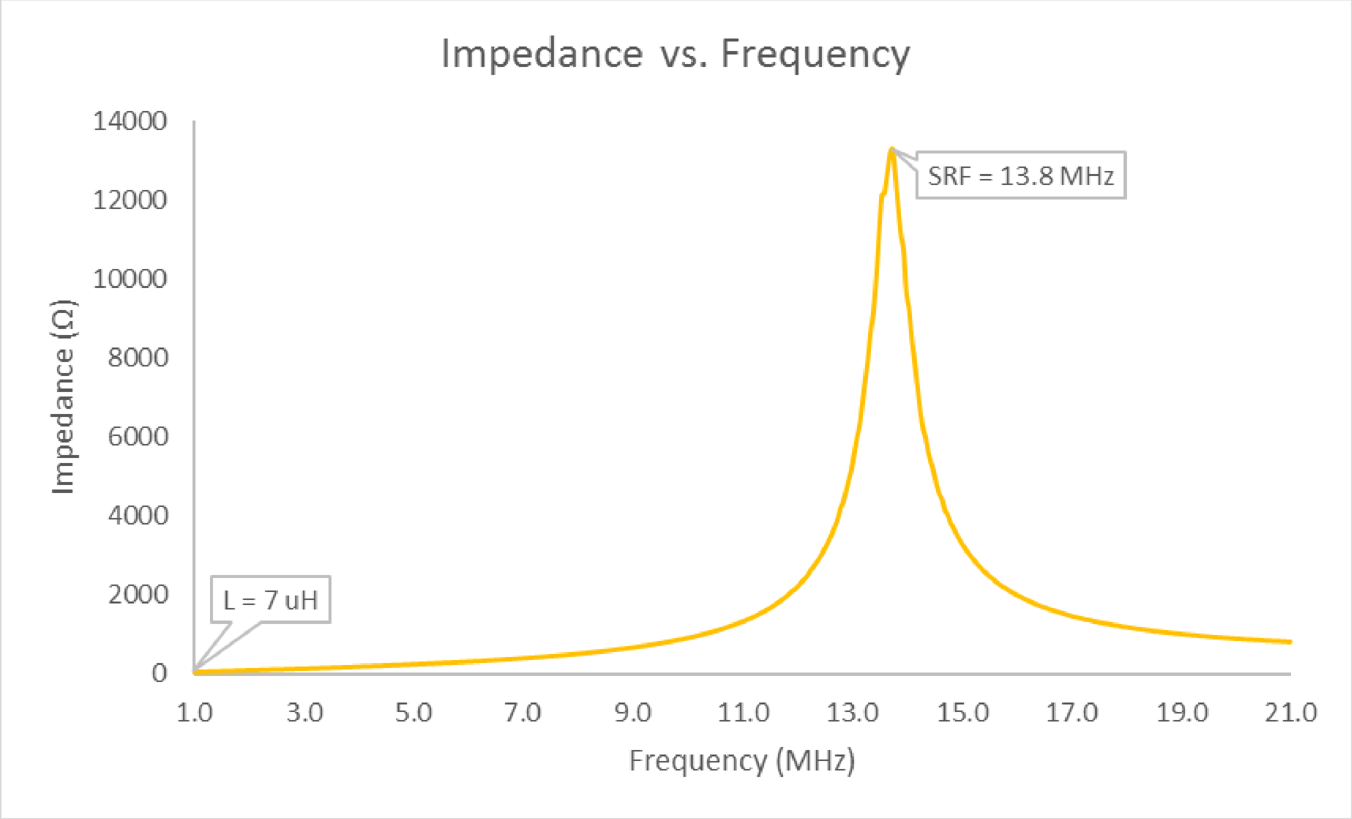
Use $C = \frac{1}{L\,(2\,\pi\,f)^2}$

In this example, $C = \frac{1}{7 * 10^{-6}\,(2 * \pi * 13.8 * 10^6)^2} = 19$ pF

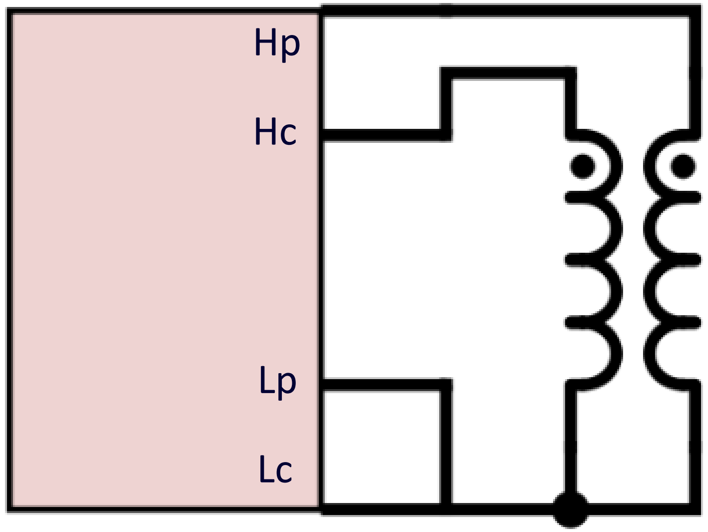
Limitations:

C can vary with frequency

L can vary with frequency (we measure L at low frequency)



Find Rp with 2 winding measurement



Rp test device construction:

Construct 1:1 transformer with same # of turns as winding of interest.

Use fine wire and no gap to reduce Q of the test transformer.

Keep windings as far apart from each other as possible to minimize mutual resistance, interwinding capacitance.

Test method:

Set test frequency to frequency of interest

Utilize 4 port LCR meter/impedance analyzer such as HP4285A

Connect DUT per schematic

Measure Rp through Lp-Rp mode

Alternate method: use manufacturer's datasheet to obtain Rp

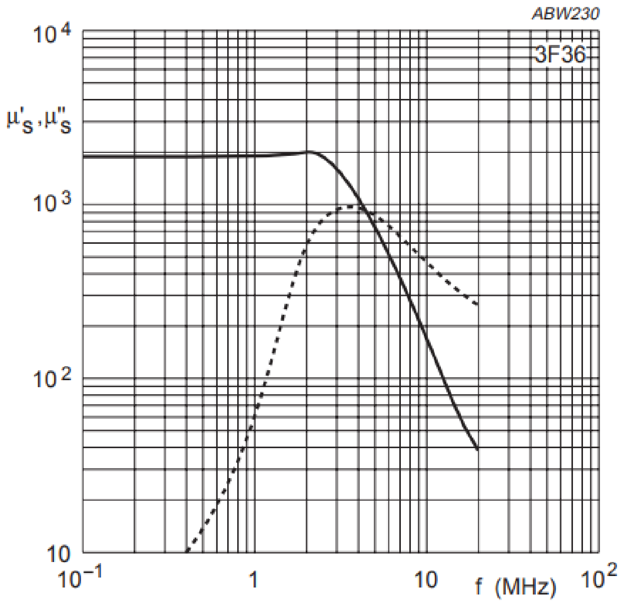


Fig.1 Complex permeability as a function of frequency.

For an ungapped core, impedance is $Z_{ungapped} = \frac{j\,\omega\,N^2}{\frac{l_e}{A_e \mu^* \mu_0}}$

μ^* is complex permeability (function of frequency)
l_e is the path length
A_e is the core area
μ_0 is the permeability of free space
N is the number of turns
ω is the frequency

$$R_p = \frac{1}{Real[\frac{1}{Z_{ungapped}}]}$$

Can obtain all parameters from datasheet and build to obtain Rp as a function of frequency.

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With Cw and Rp, can solve for Rw

Full method:

Define Z magnetic of L, Rp:

$$\frac{1}{j\,\omega\,L} + \frac{1}{R_p} = \frac{1}{Z_{magnetic}}$$

Solve for Rw in the network

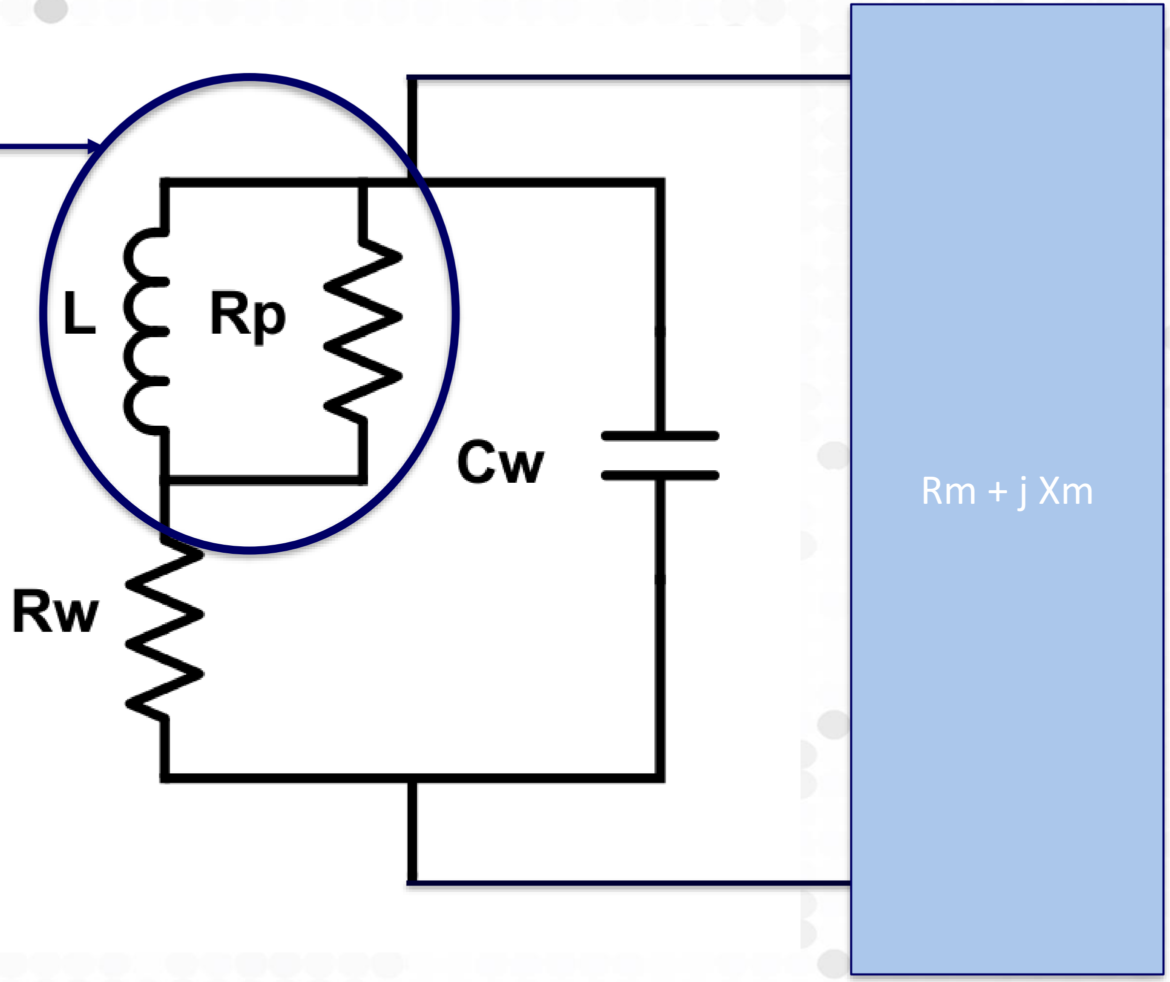
$$\frac{1}{R_w + Z_{magnetic}} + \frac{1}{\frac{-j}{\omega C}} = \frac{1}{R_m + j\,X_m}$$

$$R_w = Real\left[\frac{1}{\frac{1}{R_m + j\,X_m} + \frac{1}{\frac{j}{\omega\,C}}} - Z_{magnetic}\right]$$

Limitations:

C can vary with frequency

L can vary with frequency



With Cw and Rp, can solve for Rw

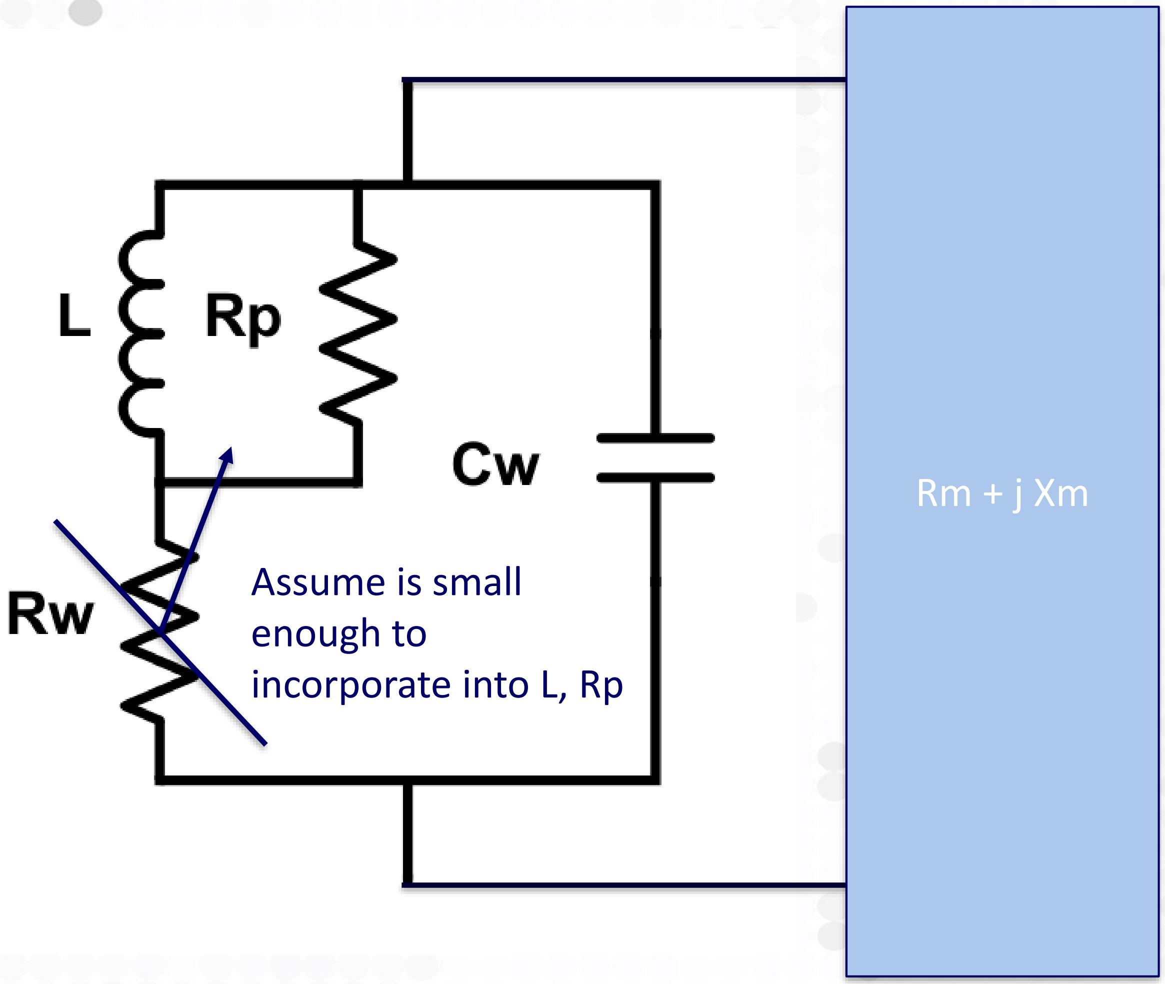
Simple method

Subtract off capacitance and Rp effect in parallel space

$$\frac{1}{Rw + j\,X_{inductor}} = \frac{1}{R_m + j\,X_m} - j\,\omega\,C - \frac{1}{R_p}$$

$$R_w = Real\left[\frac{1}{\frac{1}{R_m + j\,X_m} - j\,\omega\,C - \frac{1}{R_p}}\right]$$

****This expression is only valid when Rw is small compared to the real part of L, Rp parallel combination****



Example

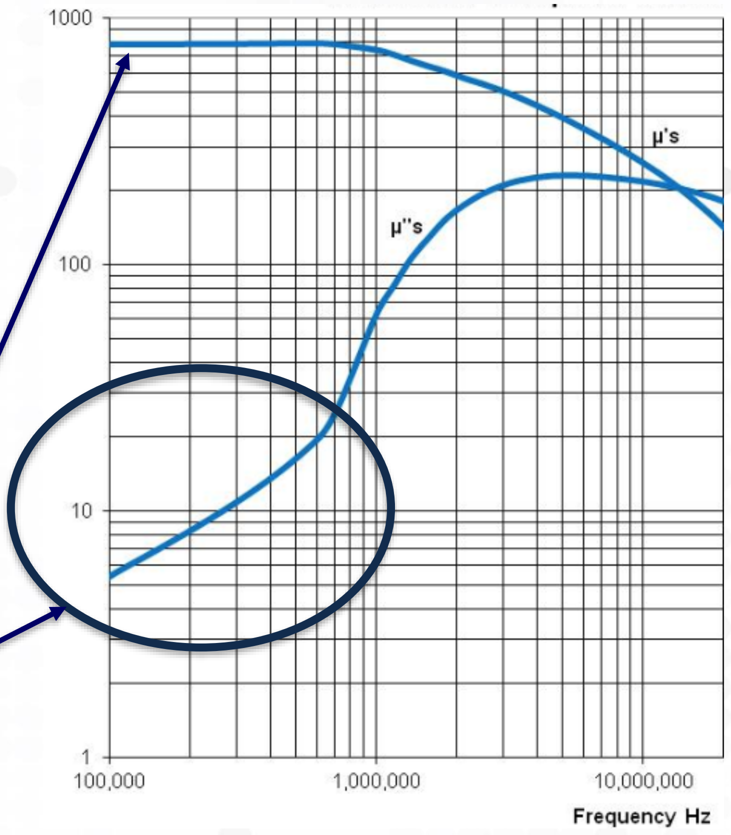
15 turn inductor on Fair-Rite 5943002701 core, measure from 100 kHz to 500 kHz in 25 kHz steps.

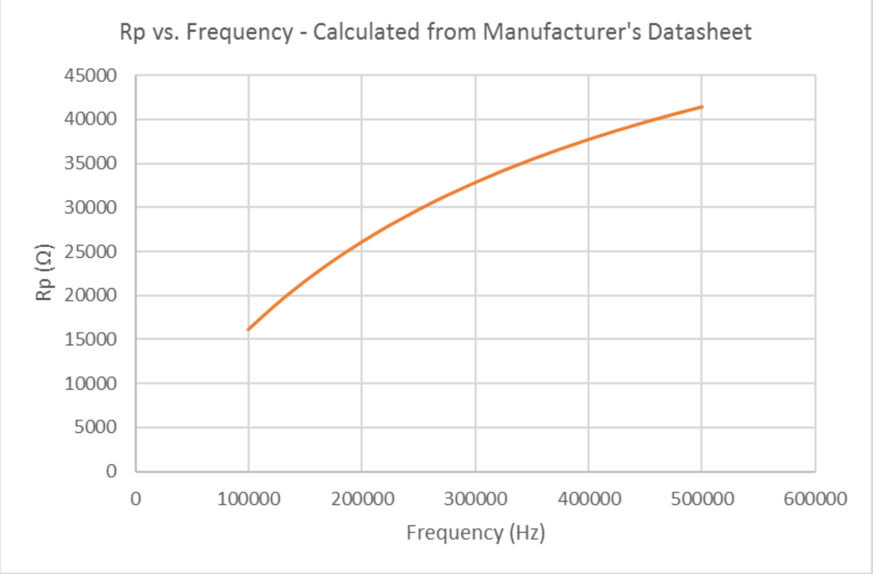
Calculate Rp from manufacturer's data:

Electrical Properties	
A_L(nH)	885 ±20%
Ae(cm^2)	0.79
ΣI/A(cm^{-1})	11.2
l_e(cm)	8.9
V_e(cm^3)	7

u' is constant in the range of interest

u'' is linear – create line to fit beginning and end point

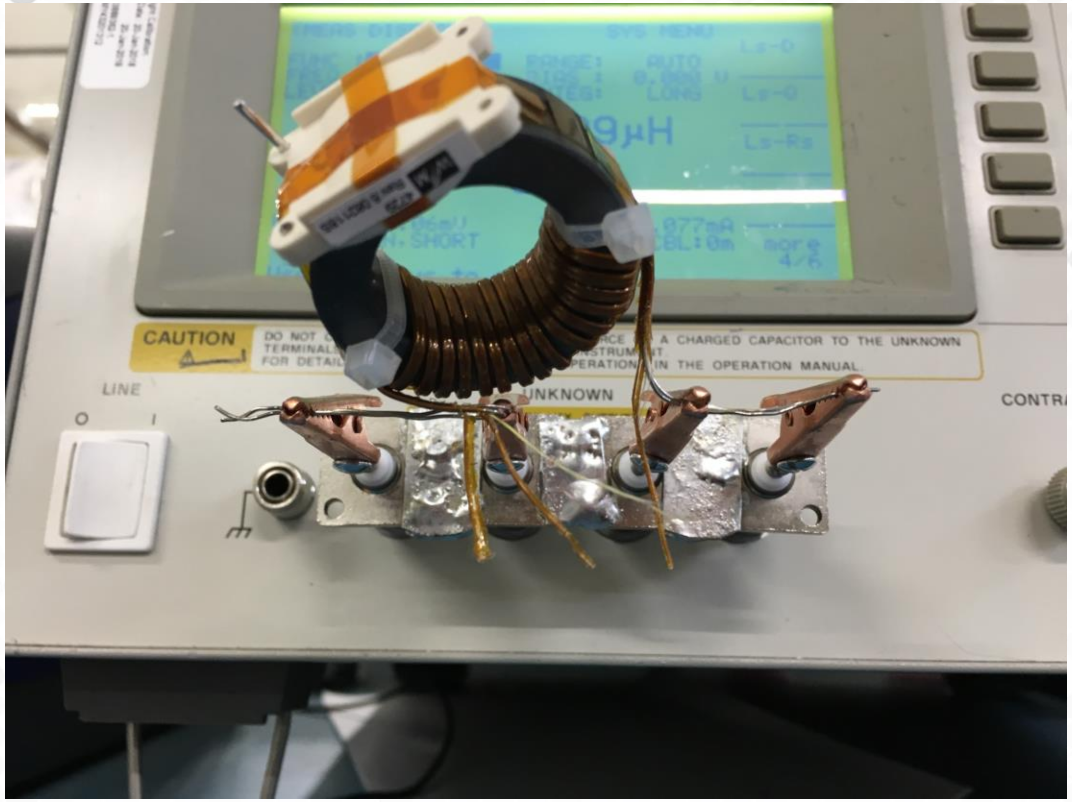


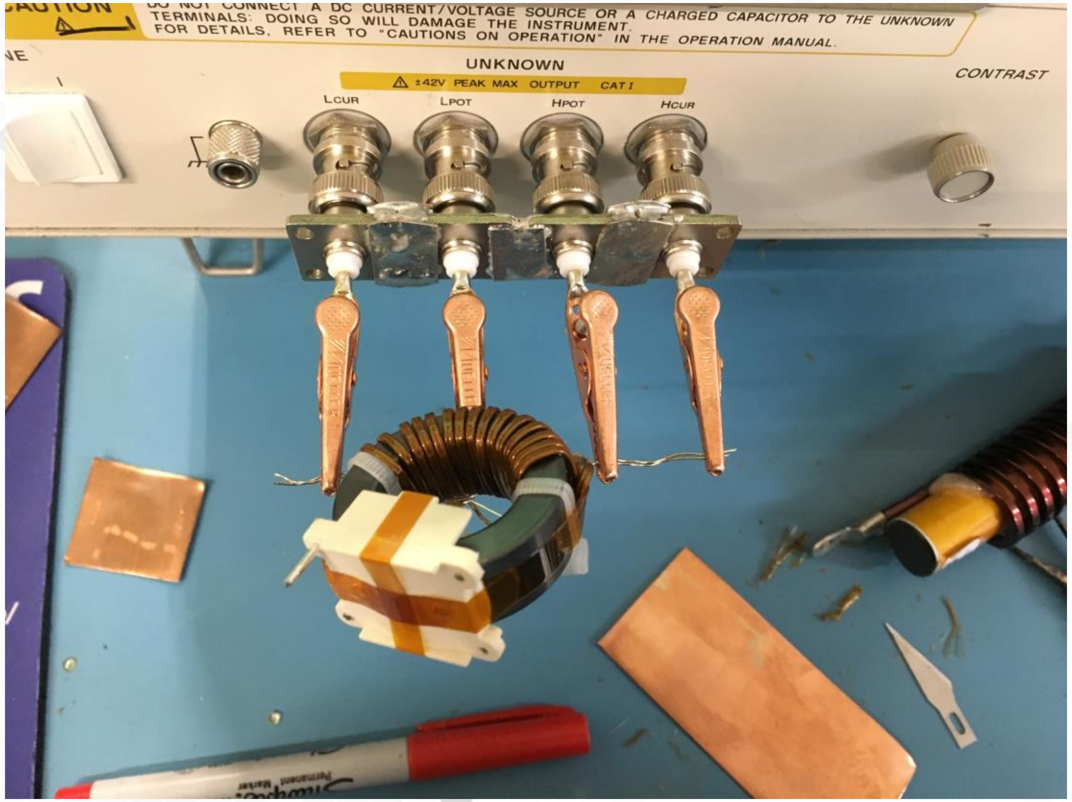


Rp increases with frequency

Example

Measure Rm and Xm on impedance analyzer - used HP4285A in example.





Use short fixture, with current injection and voltage measurement clips separate, to minimize stray resistance and inductance

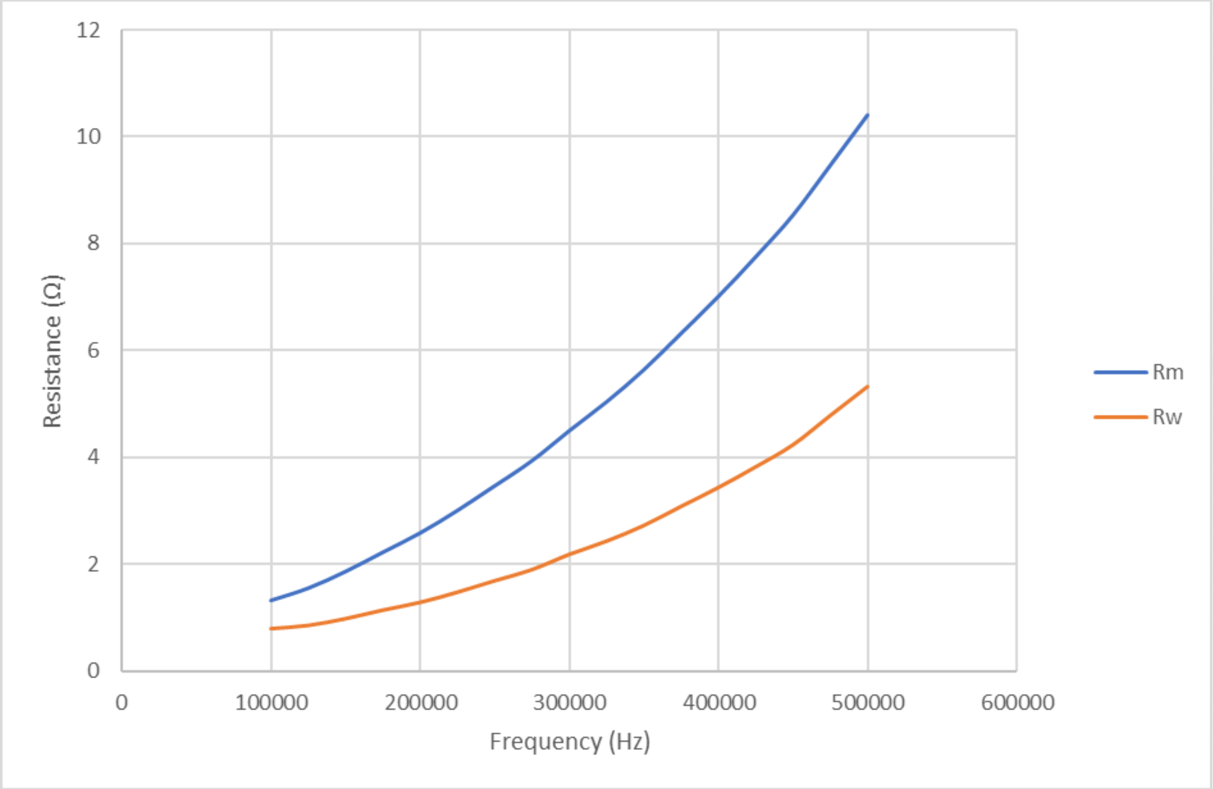
Example

Measure Rm, Xm, SRF on impedance analyzer. Use SRF, low frequency inductance, to calculate capacitance.

Plug values to formula and extract Rw.

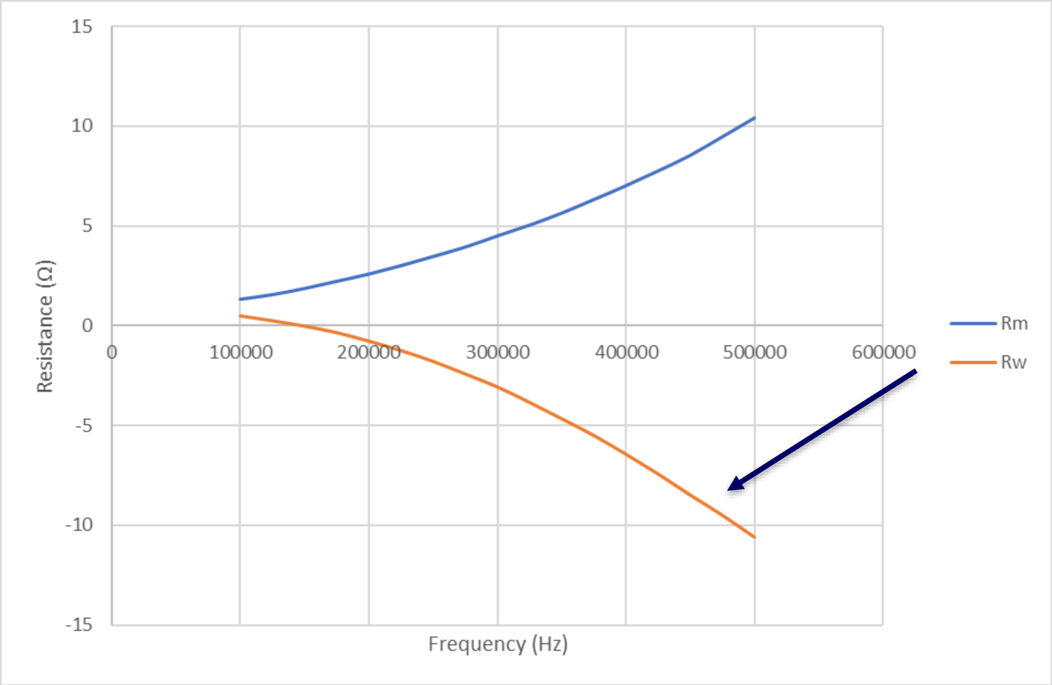
$$R_w = Real\left[\frac{1}{\frac{1}{R_m + j\,X_m} + \frac{1}{\frac{j}{\omega\,C_w}}} - Z_{magnetic}\right]$$

Physical result – Rw increases with frequency

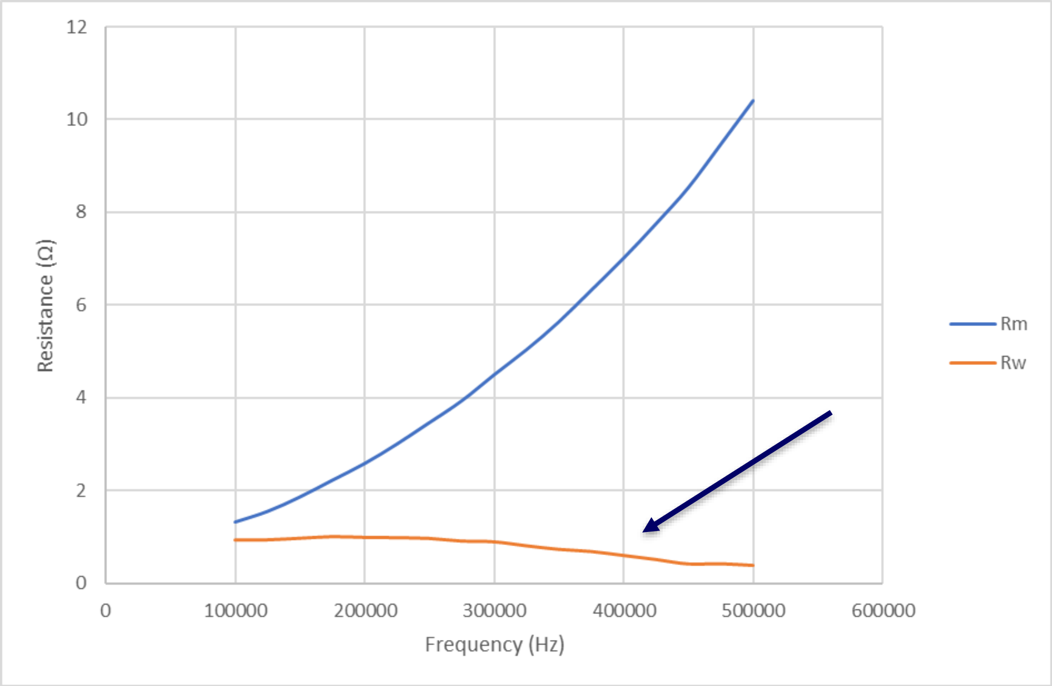


Errors

Obvious error:
extracted resistance is negative



Less obvious error:
extracted resistance trends downward – not a physical result



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REFERENCE

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

Benedict X. Foo, Aaron L.F. Stein, Charles R. Sullivan

Presented at APEC 2016