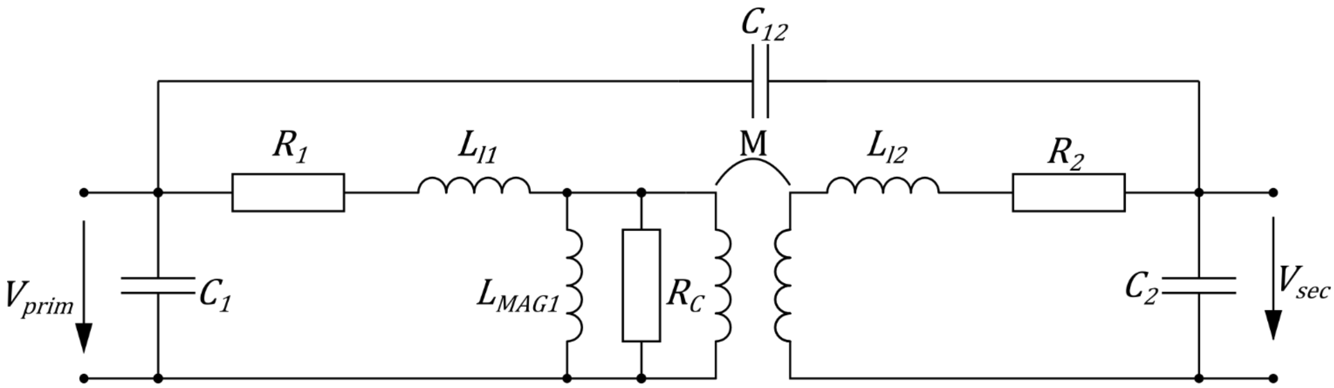
Bode 100 - Application Note

Transformer modelling



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Contact support@omicron-lab.com for technical support.

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Note: Basic procedures such as setting-up, adjusting and calibrating the Bode 100 are described in the Bode 100 user manual. You can download the Bode 100 user manual at www.omicron-lab.com/bode-100/downloads#3

Note: All measurements in this application note have been performed with the Bode Analyzer Suite V3.0. Use this version or a higher version to perform the measurements shown in this document. You can download the latest version at www.omicron-lab.com/bode-100/downloads

1 Executive Summary

This application note shows how a real transformer with its parasitic elements can be modelled with the Bode 100.
A transformer model can be used in a simulation program. The model includes parasitic elements and therefore, the behavior corresponds with the physical measurement more exactly. Furthermore, circuit models give a good overview of the power losses and their location. With the Bode 100, it is possible to design such a transformer model within a few measurements.

2 Measurement and Calculation

2.1 Used Model

The following measurements and calculations always refer to Figure 1 below unless stated otherwise.

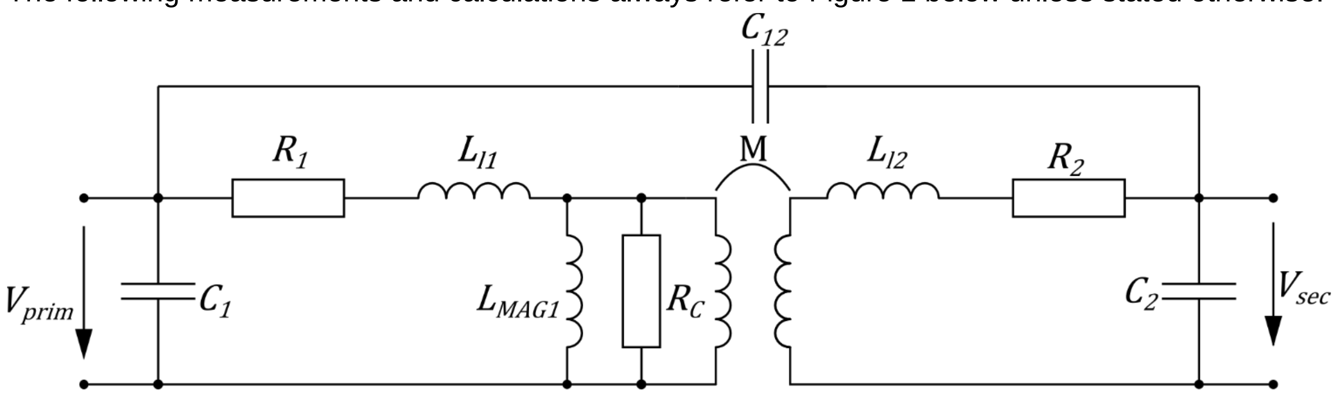

Figure 1: Used Transformer Model

R_1 … resistance of primary winding
R_2 … resistance of secondary winding
R_c … core resistance
L_{l1} … leakage inductance of primary coil
L_{l2} … leakage inductance of secondary coil
L_{MAG_1} … magnetizing inductance of primary coil
C_1 … primary intra winding capacitance
C_2 … secondary intra winding capacitance
C_{12} … interwinding capacitance

For the sake of convenience, the frequency and signal level dependent core losses are ignored.

2.2 Primary Side Measurement

In this section, the primary side's winding resistance R_1 and the two primary coils L_{l1} and L_{MAG_1} are measured. To do so, it has to be ensured that the used frequency range is low enough to keep the influence of the parasitic capacitors small. The following diagram depicts a One-Port measurement (Figure 5) showing the impedance of the exemplarily used transformer.

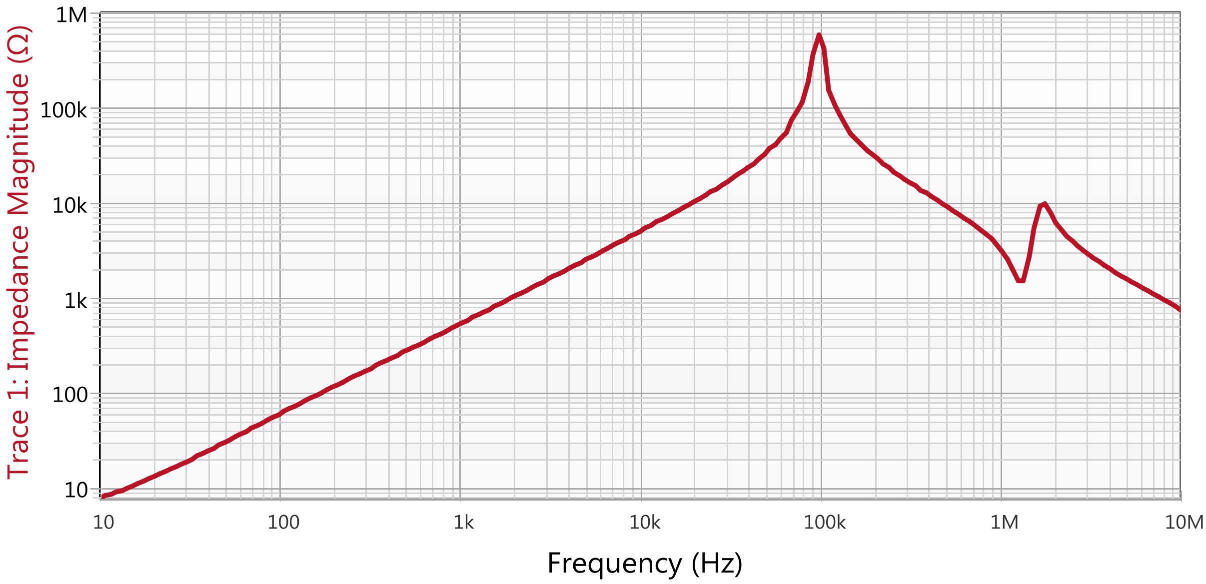

Figure 2: Frequency Response of a Transformer's Impedance

As long as the line has a continuous slope, the parasitic capacitances do not influence the measurement. Relating to the case shown in Figure 2, this means that at frequencies below $10\ kHz$ the parasitic capacitors can be neglected.
For this limitation, the circuit to be measured looks like this:

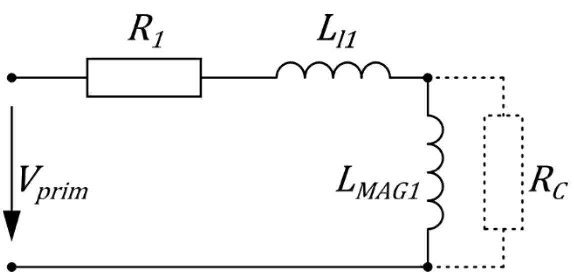

Figure 3: Equivalent Circuit with Open Secondary Coil

According to the picture, the DUT consists of a series connection of the winding resistance R_1, the primary coil's leakage inductance L_{l1} and the magnetizing inductance L_{MAG_1}. A resistor would, additionally, be connected parallel to the magnetizing inductance for modelling the core losses. For the measurement, these core losses should be kept as low as possible. As this losses are strongly dependent on the frequency and the magnetic flux density, this two parameters are decreased as much as possible. However, the measurement's sphere of interest must not have a signal to noise ratio, able to distort the measurement.

Low core losses mean a big core resistance R_C. Hence, the equivalent circuit is a series connection of R_1, L_{l1} and L_{MAG_1}, as derived in equation (1) and (2).
The following calculation shows the input impedance of the primary side Z_1 with already separated real and imaginary part. The calculation shows the dependency on the core resistance.

$$Z_1 = R_1 + \frac{\omega^2 {L_{MAG_1}}^2 R_C}{R_C^2 + \omega^2 {L_{MAG_1}}^2} + j\omega \left(L_{l1} + \frac{L_{MAG_1}}{1 + \frac{\omega^2 {L_{MAG_1}}^2}{R_C^2}} \right) \quad (1)$$

$$\rightarrow \lim_{R_C \to \infty} (Z_1) = R_1 + j\omega \cdot (L_{l1} + L_{MAG_1}) \quad (2)$$

2.2.1 Measurement of Primary Winding Resistance R_1

At DC voltage, the winding resistance can be measured easily. For very low winding resistances, a 4-wire sensing should be conducted to compensate the failures made with the measuring device. If the real part isn't too low related to the imaginary part, the winding resistance measurement can directly be performed by the Bode 100.

Measurement Setup

The output of the Bode 100 simply has to be connected to the transformers primary side. The secondary side is left open circuited.

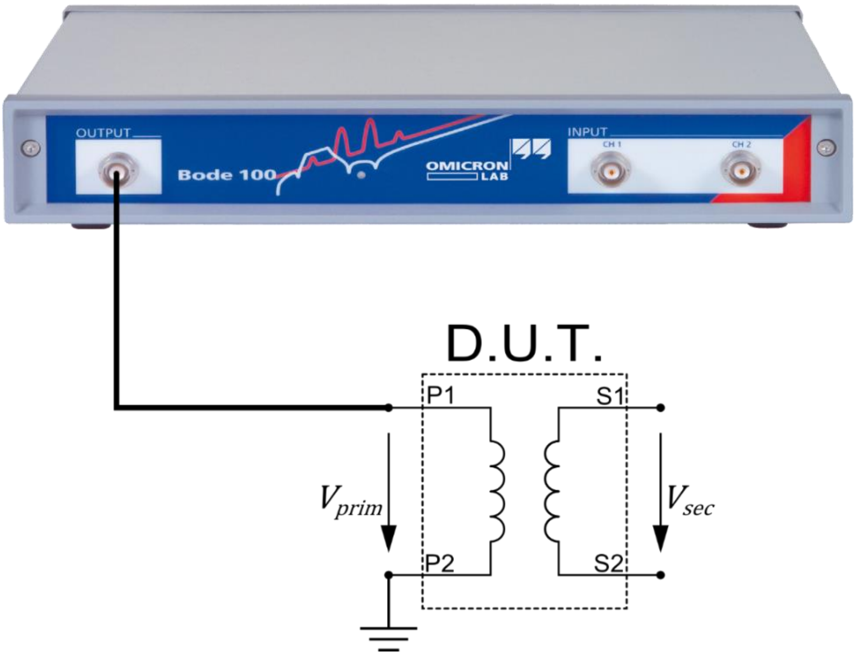

Figure 4: Measurement Setup for Winding Resistance Measurement

P1… primary side's hot end
P2… primary side's cold end
S1… secondary side's hot end
S2… secondary side's cold end

Device Setup & Calibration

The impedance is measured with a One-Port measurement.

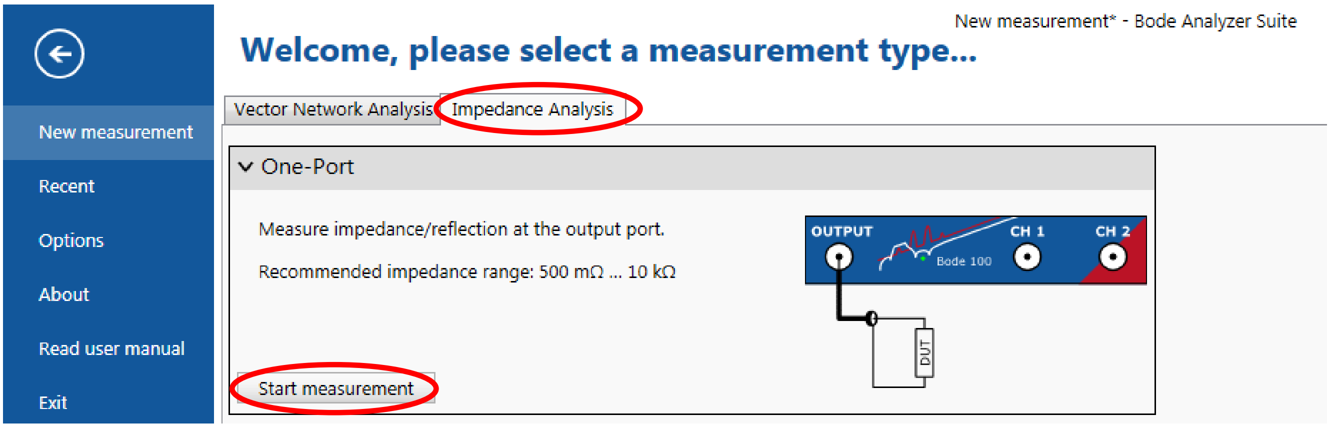

Figure 5: Start menu

The settings for this impedance measurement are:

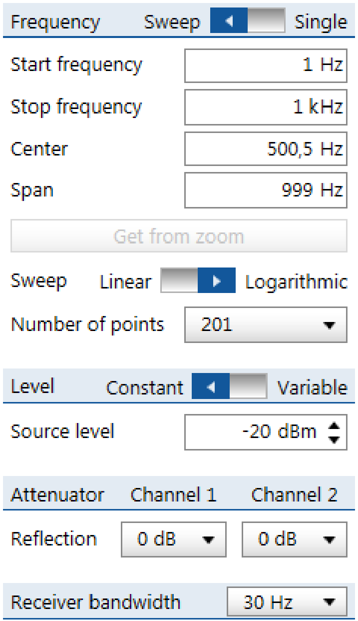

Figure 6: Settings for the measurement

It is important that the start frequency starts at a low frequency like e.g. $1\ Hz$ for the winding resistance measurement.

To aviod core losses, the signal level should be as low as possible as mentioned before. In the case given, -20 dBm have been chosen. If the level would be decreased more, the measured impedance would interfere with signal noise. If there are too many ripples around the point of interst, the signal level has to be increased.

For the measurement of the winding resistance, “Measurement” is set to “Impedance” and “Format” is set to “Rs”.

For better measurement results, a user-range calibration should be performed prior the measurement.

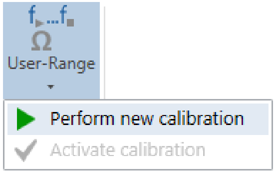

Figure 7: perform user-range calibration

Results

After doing a single measurement, the following result was obtained:

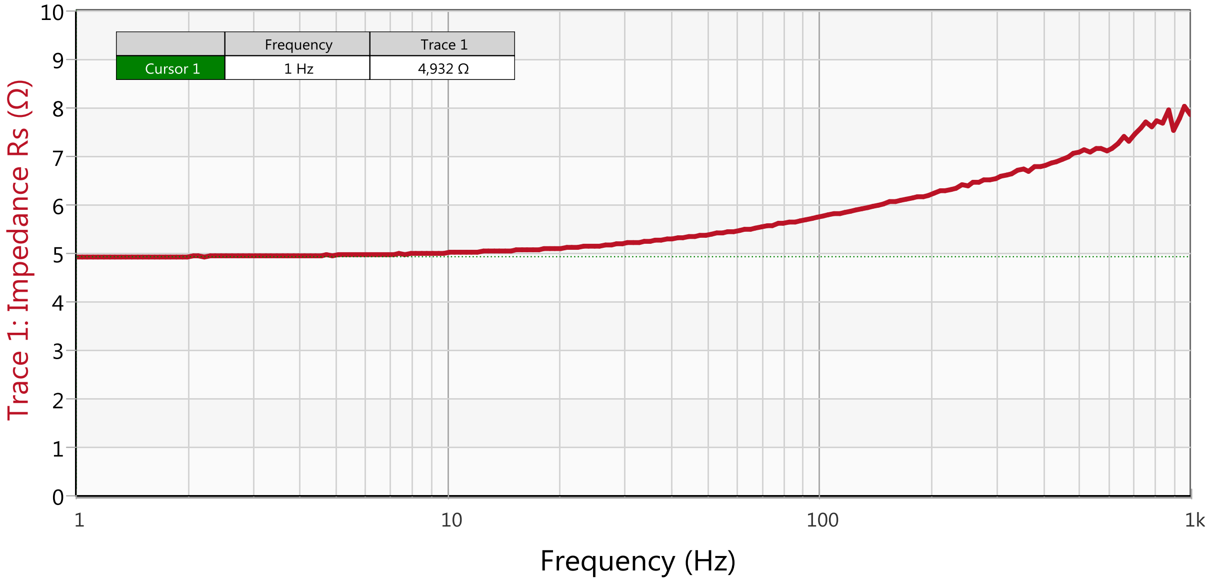

Figure 8: Primary Winding Resistance Measurement

The curve shows a high ripple at frequencies over 100 Hz. But for the winding resistance measurement, only the equivalent series resistant at 1 Hz is required.
By typing this frequency into the cursor window, the cursor jumps to 1Hz and states the winding resistance of the primary coil R_1.
The winding resistance of the measured transformer is $R_1 = 4{,}93\ \Omega$.

2.2.2 Measurement of Primary Coils L_{l1} & L_{MAG_1}

The series coil inductance can also be measured in the *One-Port* measurement type. In order to do this, “Format” has to be changed to “Ls”.
All the other settings are the same as for the winding resistance measurement. (Section 2.2.1)

By doing a single sweep the following result was obtained:

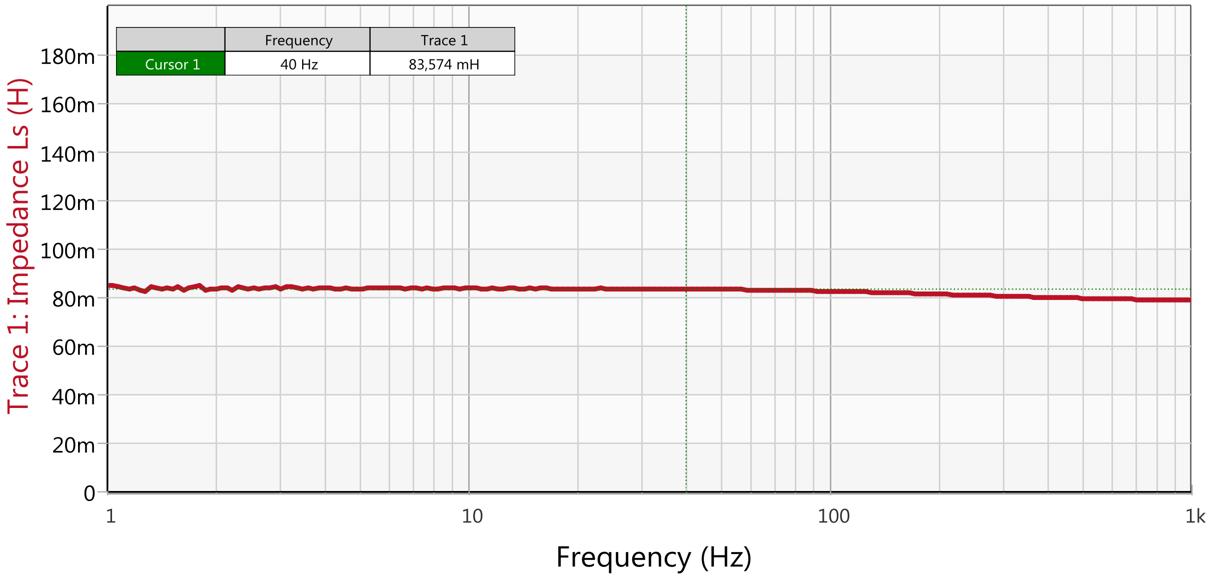

Figure 9: Primary Coil Value Measurement

With the aid of the cursor, an inductance at a specific frequency can be measured. According to (1), the imaginary part is decreasing for higher frequencies because the core resistance R_C is decreasing. So, the inductance should be measured at a point with a low ripple value and before the inductance is decreasing noticeably. The measured inductance at 40 Hz is 83.57 mH.
This inductance is the series circuit of the primary coil's leakage inductance L_{l1} and magnetizing inductance L_{MAG_1}. Henceforth, this inductance is called L_1. ($L_1 = L_{l1} + L_{MAG_1}$)
To get the individual values of L_{l1} and L_{MAG_1}, a gain-measurement is performed.
Therefore, the measurement conditions have to be changed like depicted below.

Measurement Setup

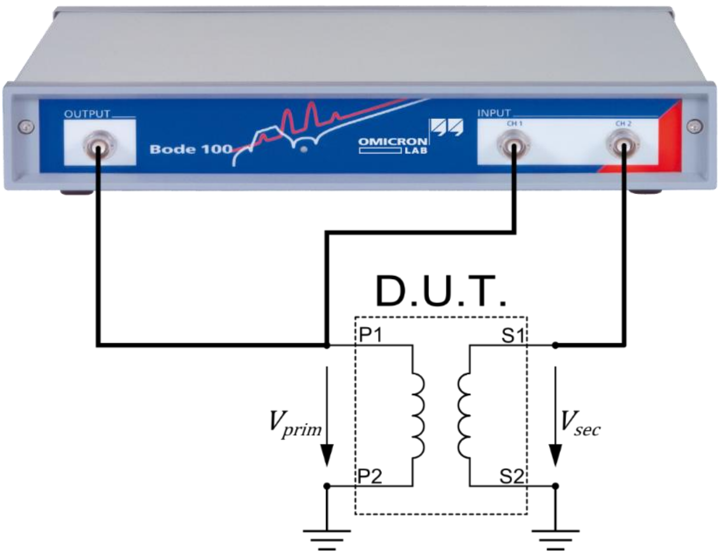

Figure 10: Measurement Setup for L_{l1} & L_{MAG_1} Measurement

The output of the Bode 100 as well as Channel 1 are connected to the primary side of the DUT. Channel 2 is connected to the secondary side of the DUT.

Device Setup and Calibration

For the example measurement, the following settings are used:
For the gain measurement, the Gain / Phase mode has to be chosen.

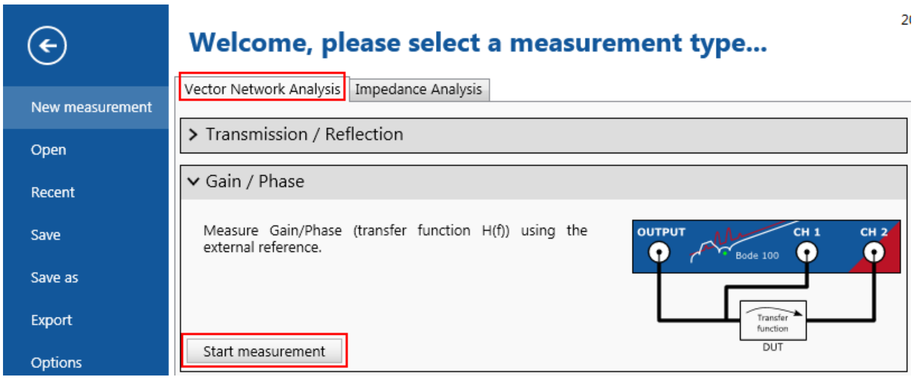

Figure 11: Start menu

The frequency range should at least contain the upper frequency limit used for the measurements before but to speed up the measurement the start frequency can be increased.

For the gain measurement, the same input signal level is used as for the measurements before. In the exemplary case, the -20 dBm are used again.

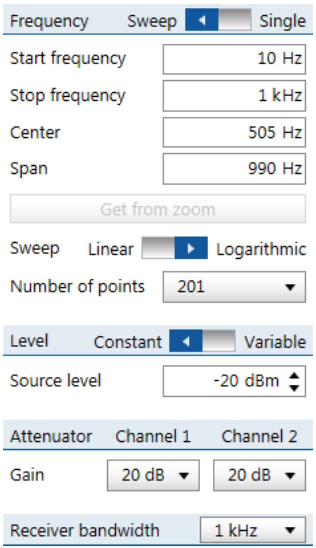

Figure 12: Settings for the measurement

The “Format” is set to “Magnitude”.

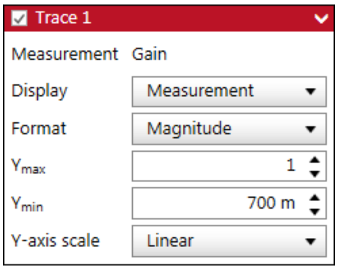

Figure 13: Settings Trace 1

Before the measurement is performed, a User-Range THRU calibration should be conducted.

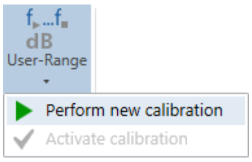

Figure 14: User-Range Calibration icon

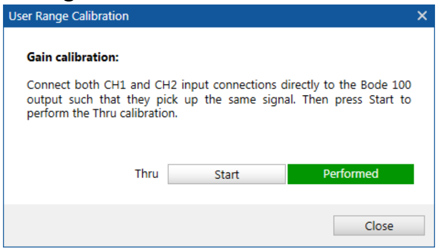

Figure 15: User Range Calibration window

Therefore, the DUT has to be replaced with a short circuit and after the calibration, the DUT is connected again.

Results

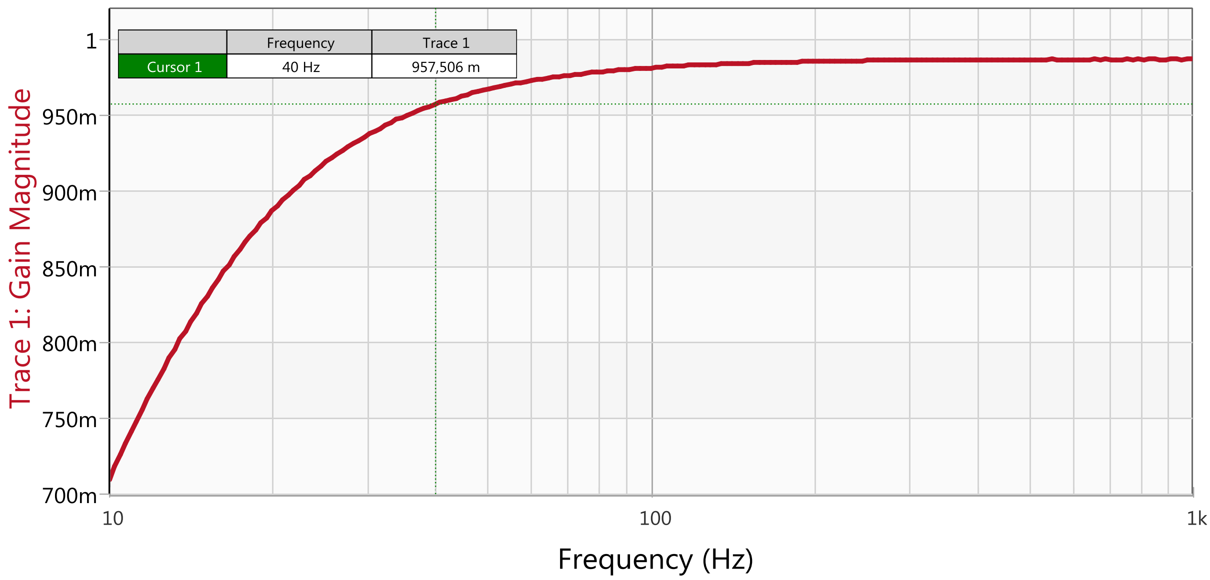

Figure 16: Gain Measurement of the Examined Transformer

The gain is measured at the frequency where the series inductance L_1 is measured (40 Hz).
By typing in the frequency into the cursor-frequency window, the gain at this specific frequency is stated.

The gain measured with the Bode 100 is calculated by: $G = \frac{V_{CH2}}{V_{CH1}}$

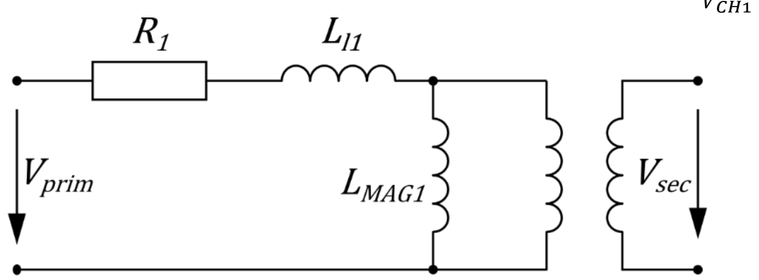

Figure 17: Equivalent Circuit of the DUT during Gain Measurement

By taking a look at the equivalent circuit of the currently measured DUT (Figure 17), the gain can be calculated by:

$$G = \frac{|V_{CH2}|}{|V_{CH1}|} = \frac{\omega L_{MAG\,1}}{\sqrt{R_1^2 + (\omega L_1)^2}} \cdot \frac{1}{a} \quad (3)$$

… where $a = \frac{N_1}{N_2}$ (turns ratio)

Note: Due to our 1:1 transformer, we idealized our a to 1.

Solving the equation for $L_{MAG\,1}$, results in:

$$L_{MAG\,1} = \frac{Ga}{\omega} \cdot \sqrt{R_1^2 + (\omega L_1)^2} \quad (4)$$

Afterwards, the leakage inductance L_{l1} can be calculated by:

$$L_{l1} = L_1 - L_{MAG\,1} \quad (5)$$

For the DUT, the calculated values are: $L_{MAG\,1} = 82.2\,mH$ $L_{l1} = 1.4\,mH$

2.3 Secondary Side Measurement

This section regards the measurements of the parameters on the secondary side which are the winding resistance R_2 and the leakage inductance L_{l2}.

2.3.1 Measurement of Secondary Winding Resistance R_2

The measuring principle is exactly the same as described for the measurement of the primary winding. The measurements are just performed on the opposite side.

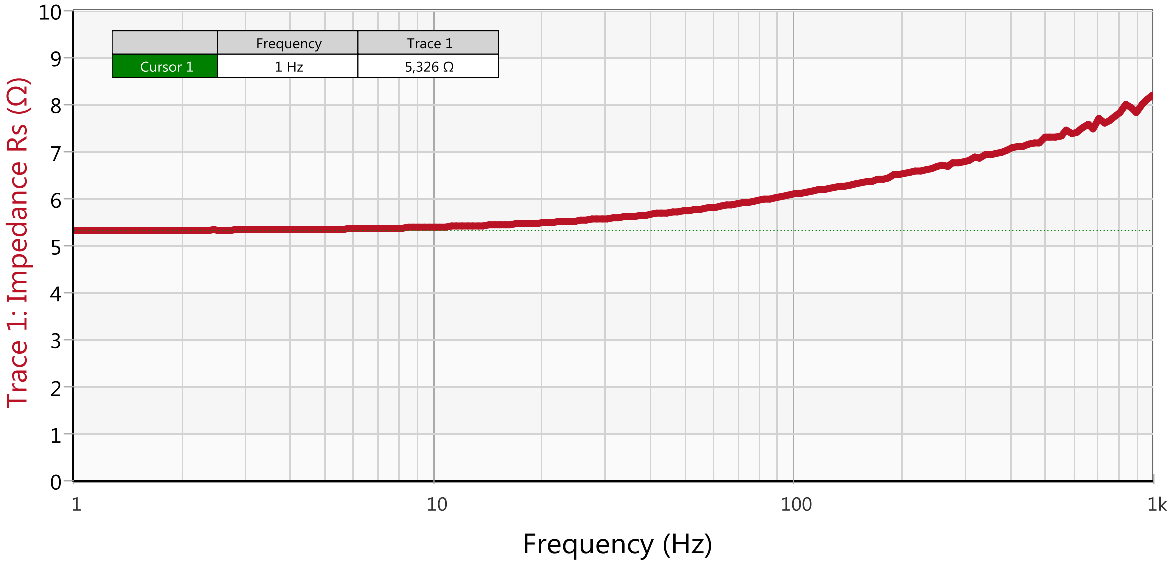

Figure 18: Secondary Winding Resistance Measurement

The measured resistance R_2 at $1\,Hz$ is $5.33\,\Omega$.

2.3.2 Measurement of Secondary Leakage Coil L_{l2}

By changing the “Format of the measurement from “Rs” to “Ls”, the equivalent series inductance gets displayed. This inductance is composed of the secondary leakage inductance and the magnetizing inductance. The magnetizing inductance has already been measured at the primary side. Hence, the magnetizing inductance of the secondary side $L_{MAG\,2}$ can be calculated by transforming.

$$L_{MAG\,2} = L_{MAG\,1} \cdot \left(\frac{N_2}{N_1}\right)^2 \qquad (6)$$

After a single sweep, the following result was obtained:

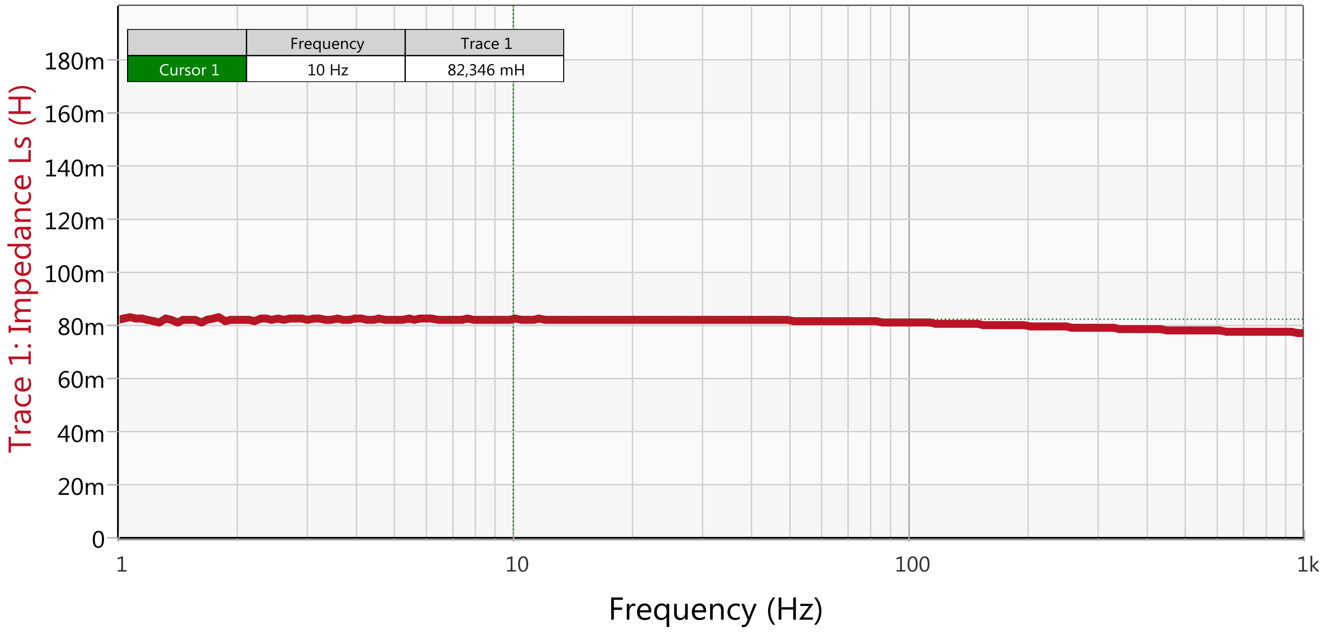

Figure 19: Secondary Coil Measurement

Again, the inductance should be measured at a point with low ripple and before the inductance is decreasing. In the example, the inductance is measured at 10 Hz & the measured inductance L_2 is 82.3 mH.

Now, the leakage inductance L_{l2} can be calculated by:

$$L_{l2} = L_2 - L_{MAG\,2} \qquad (7)$$

For the DUT the calculated leakage inductance is $L_{l2} = 0.15\,mH$.

2.4 Capacitance Measurement

In this section, it is described how the three parasitic capacitances of the used transformer model (Figure 1) are measured.

2.4.1 Measurement of Interwinding Capacitance C_{12}

To measure the interwinding capacitance, both, the primary and the secondary side are short circuited. Thus, the following equivalent circuit is emerged.

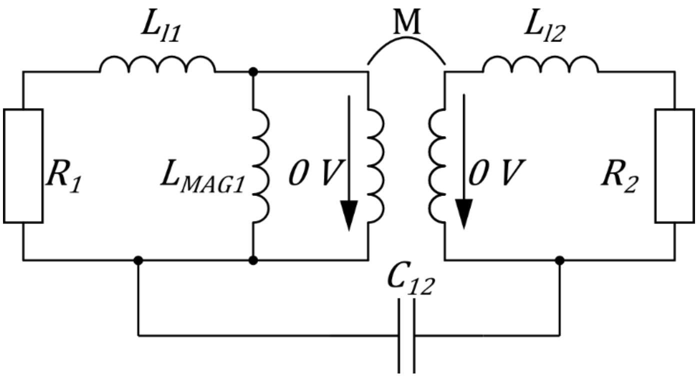

Figure 20: Equivalent Circuit for Interwinding Capacitance Measurement.

According to the shown equivalent circuit, the capacitance C_{12} can directly be measured because the both side shortened transformer does not have a function anymore.

Measurement Setup

Regarding the things stated before, the measurement setup has to look like this:

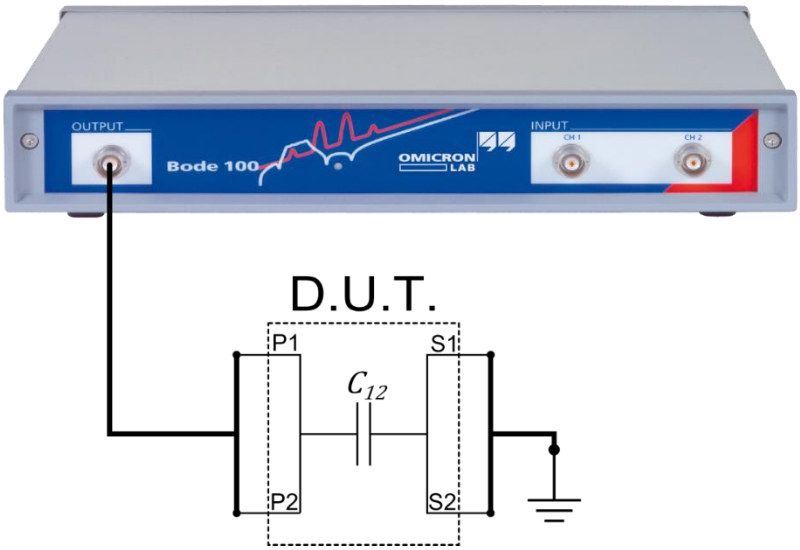

Figure 21: Measurement Setup for the Interwinding Capacitance Measurement

Device Setup & Calibration

For the capacitance measurement, the frequency sweep method is used, because with this method it is possible to see in which capacitance range C_{12} is alternating depending on the frequency.
The capacitance can be measured more exactly at higher frequencies. Thus the sweep can start at higher frequencies. The higher the output level of the Bode 100 the higher is the accuracy of the measurement. So, choose the output level as high as possible, according to the specification of the used transformer's datasheet.

For the exemplary measurement the following settings are used:

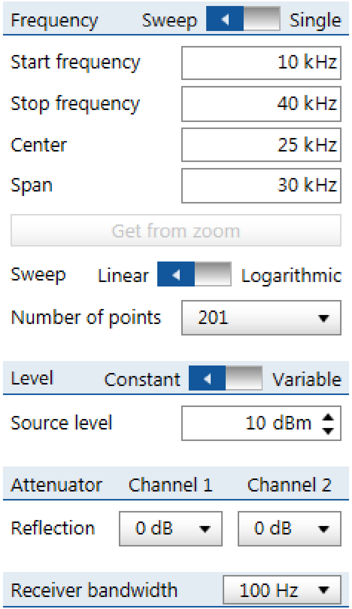

Figure 22: Settings for the measurement

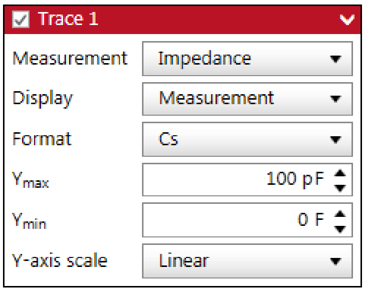

Figure 23: Settings Trace 1

Before the measurement is conducted, a user-range calibration is recommended (see Figure 7).

Results

A single sweep leads to the following curve:

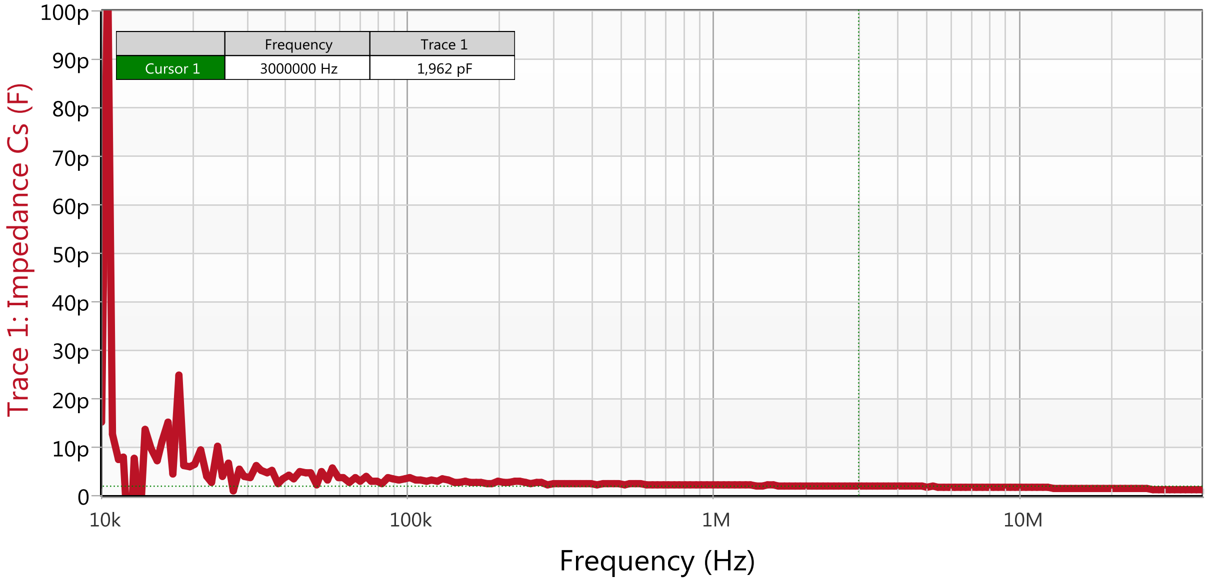

Figure 24: Interwinding Capacitance Measurement

The capacitance should be measured in a frequency range, with a constant capacitance area. The interwinding capacitance C_{12} of the DUT, measured at $3\ MHz$, is $C_{12} = 1{,}96\ pF$

2.4.2 Measurement of Primary Interwinding Capacitance C_1

To measure the primary interwinding capacitance, the secondary side is short circuited. The cold end of the transformers primary side is connected to the secondary side. After that, the equivalent circuit of the DUT looks like this:

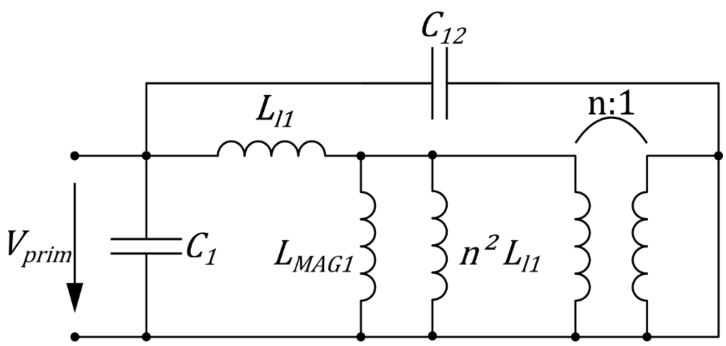

Figure 25: Equivalent Circuit for Interwinding Capacitance C_1 Measurement

In the picture above, the winding resistances are neglected. This can be done because the frequencies used for this measurement are very high. Hence, the coil's impedance is many times greater than the winding resistance's.

This circuit can be consolidated to a parallel resonant circuit like shown in the following picture.

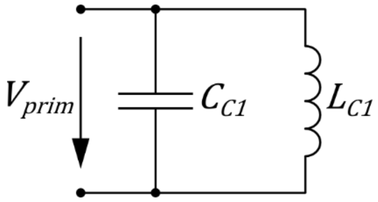

Figure 26: Consolidated Parallel Circuit for C_1 Measurement

The combined components are calculated by:

$$C_{C1} = C_1 + C_{12} \tag{8}$$

$$L_{C1} = L_{l1} + \frac{L_{MAG_1} \cdot n^2 L_{l2}}{L_{MAG_1} + n^2 L_{l2}} \tag{9}$$

For the used transformer, L_{C1} is:

$$L_{C1} = 1{,}4\,mH + \frac{82.2\,mH \cdot 0.15\,mH}{82.2\,mH + 0.15\,mH} = 1.8\,mH$$

By measuring the impedance of this parallel resonant circuit, the resonant frequency can be figured out.

Measurement Setup

The used transformer is shortened on the secondary side. The cold end of the primary side is connected to the shortened secondary side as stated before. Afterwards the output signal of the Bode 100 is applied to the primary side. Following this, the measurement setup has to look like this:

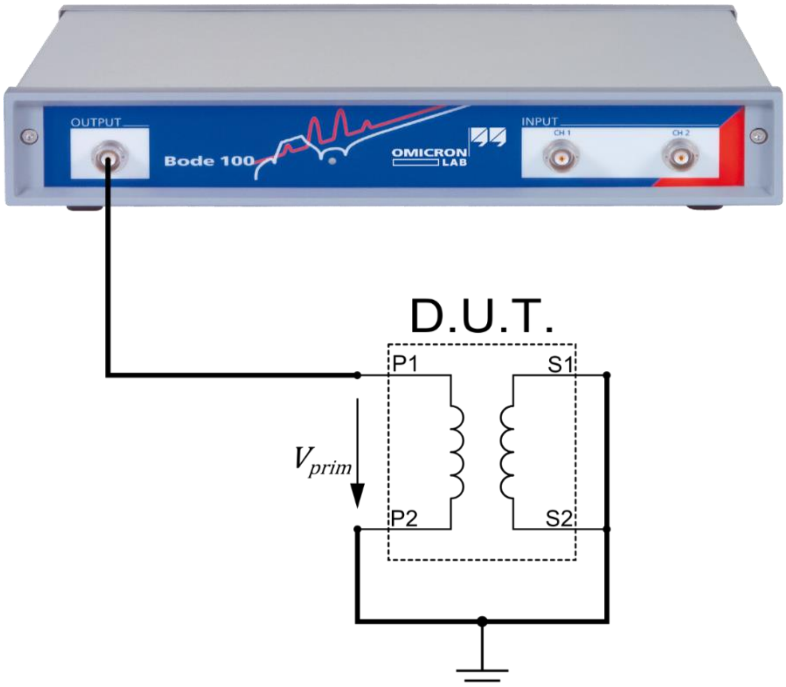

Figure 27: Measurement Setup for Primary Interwinding Capacitance Measurement

Device Setup and Calibration

As the resonant frequency has to be detected, the frequency range could begin at the kHz range. Because the actual resonant frequency isn't known, the stop frequency is chosen to be the maximal available frequency.

The settings used are stated below:

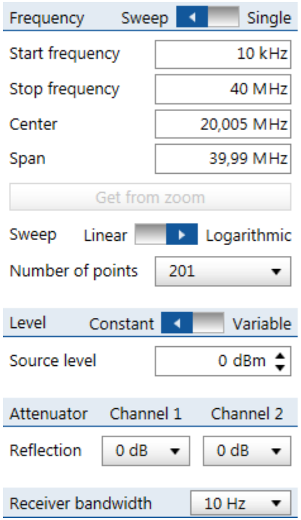

Figure 28: Settings for the measurement

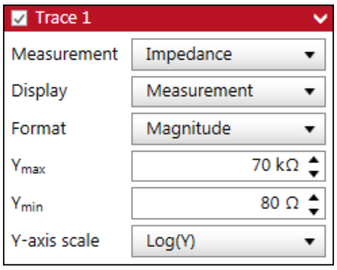

Figure 29: Settings Trace 1

Before the measurement is performed, it is advised to perform a user calibration (see Figure 7).

Results

After doing a single measurement, the following result was obtained:

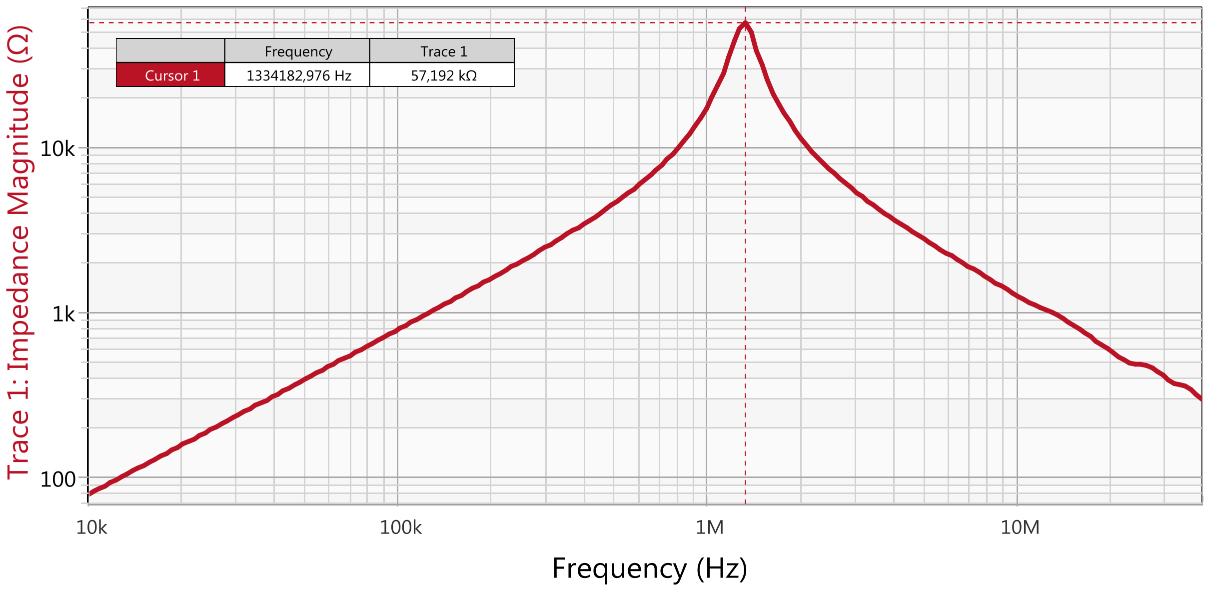

Figure 30: Resonant Frequency Measurement for Interwinding Capacitance C_1

The capacitance of the parallel circuit is now calculated by:

$$C_{C1} = \frac{1}{\omega^2 L_{C1}} \quad (10)$$

Hence, the intrawinding capacitance is:

$$C_1 = \frac{1}{(2\pi \cdot 1.334\,MHz)^2 \cdot 1.8\,mH} - 1.96\,pF = 5.95\,pF$$

2.4.3 Measurement of Secondary Interwinding Capacitance C_2

The procedure of measuring the secondary interwinding capacitance C_2 is the same as for the primary intrawinding capacitance measurement described in the section before. The only difference is the measurement setup.
Now, the primary side has to be shortened and the impedance is measured at the secondary side. The cold end of the secondary side now is connected to the shortened primary side.
Following this, the measurement setup has to look like the schematic below.

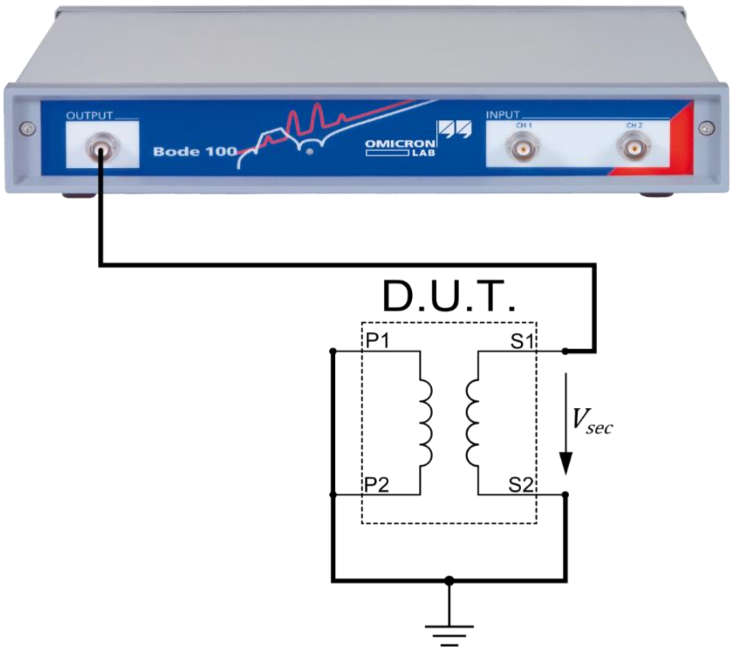

Figure 31: Measurement Setup for Secondary Interwinding Capacitance Measurement

The equivalent circuit of the DUT looks like this:

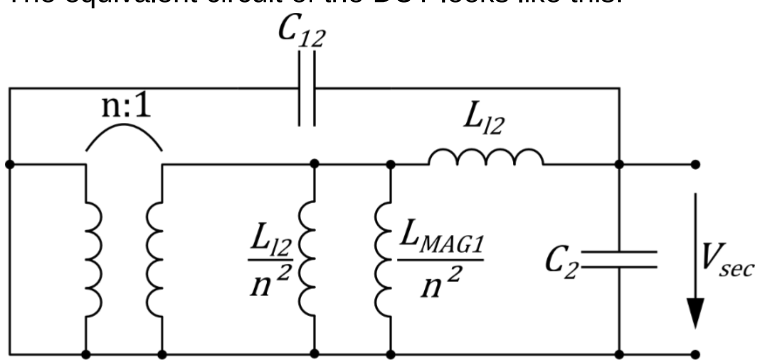

Figure 32: Equivalent Circuit for Interwinding Capacitance C_2 Measurement

The winding resistances are neglected and the components were consolidated as described in the section before.

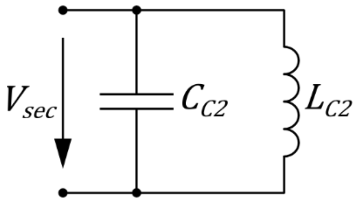

Figure 33: Consolidated Parallel Circuit for C_1 measurement

The combined components of the parallel circuit are calculated by:

$$C_{C2} = C_2 + C_{12} \tag{11}$$

$$L_{C2} = L_{l2} + \frac{L_{MAG_1} \cdot L_{l1}}{n^2 \cdot (L_{MAG_1} + L_{l1})} \tag{12}$$

For the used transformer, L_{C2} is:

$$L_{C2} = 0.15\,mH + \frac{82.2\,mH \cdot 1.4\,mH}{(82.2\,mH + 1.4\,mH)} = 1{,}53\,mH$$

The device settings are the same as for the primary interwinding capacitance measurement in section 2.4.2 on page 17.

Result

Doing a single sweep, the following result is obtained for the exemplary transformer.

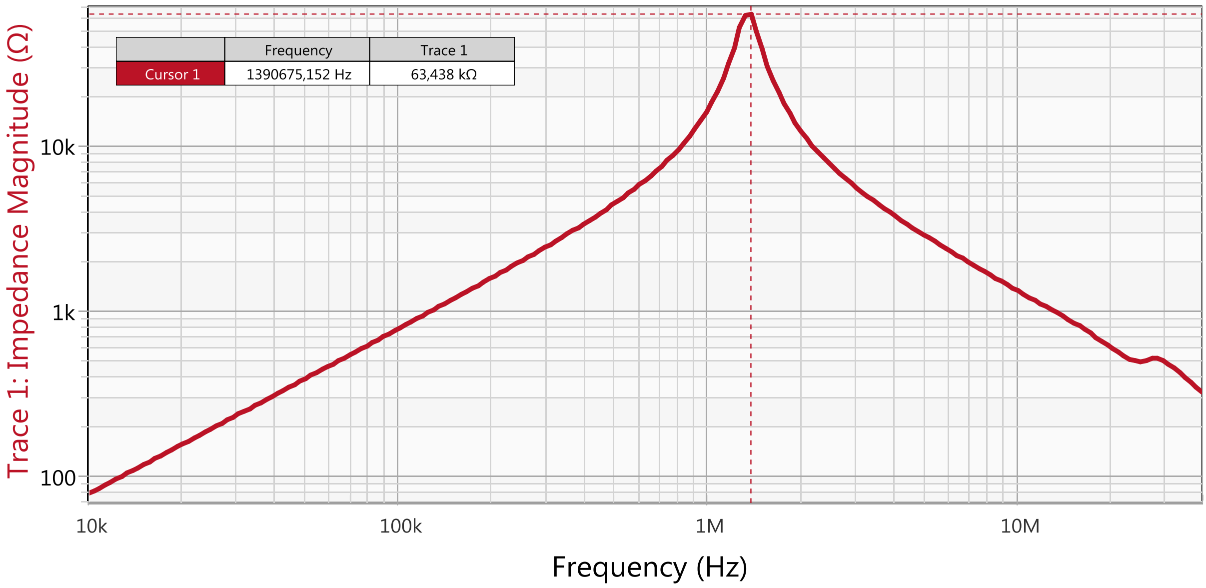

Figure 34: Resonant Frequency Measurement for Interwinding Capacitance C_2

The calculation of the secondary interwinding capacitance is analogue to the primary capacitance. Hence, the following values are obtained:

$$C_2 = \frac{1}{\omega^2 L_{C2}} - C_{12} = \frac{1}{(2\pi \cdot 1.39\ MHz)^2 \cdot 1.53\ mH} - 1.9\ pF = 6.67\ pF$$

References

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