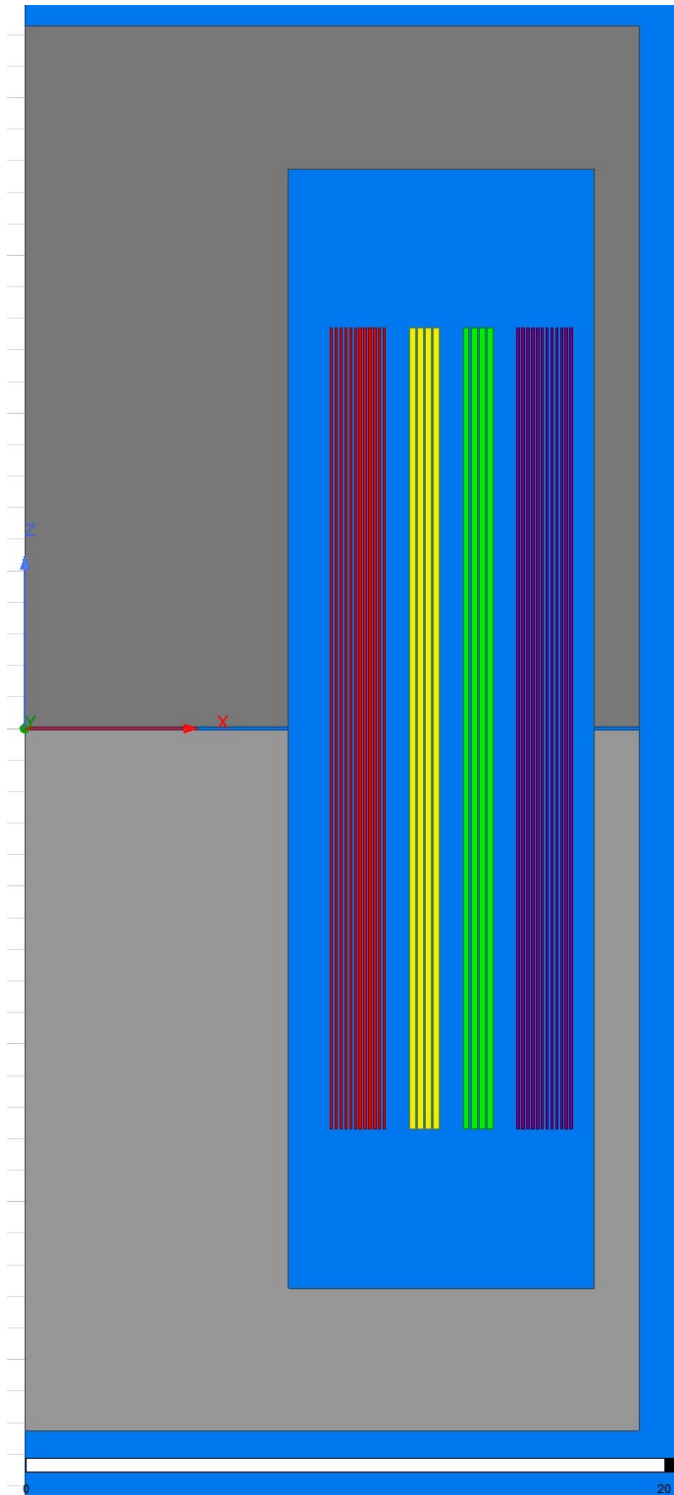


Four-Winding Transformer Model Coefficient Extraction from FEA Data

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Winding 1: 12 T 0.003" by 1" copper foil

Winding 2: 4 T 0.007" by 1" copper foil

Winding 3: 4 T 0.007" by 1" copper foil

Winding 4: 12 T 0.003" by 1" copper foil

2mil Nomex between each layer.

10 layers 2 mil Nomex between windings. (Nomex modeled as 3 mil based on measurements of wound bobbin)

Core: ETD49-25-16 3C97

Gap: 3 mil

Bobbin: TDK B66368B1020T001

Fig. 1. Transformer construction details.

The impedance matrix results of Maxwell 2D simulation ETD49-25-16_12-4-4-12T_10kHz_10MHz.aedt were exported to file: ETD49-25-16_12-4-4-12T_10kHz_10MHz_Setup1.txt.

In order to make parsing for Mathcad easier, that text file was modified and saved as ETD49-25-16_12-4-4-12T_10kHz_10MHz.txt. The following changes were made:

1. The first frequency row starts in the first column like the others.
2. Hz was from the frequencies.
3. Commas were replaced with tabs.
4. Blank rows at the end were deleted.

Read the data file.

$Maxwell := \text{READFILE}(\text{"ETD49-25-16_12-4-4-12T_10kHz_10MHz.txt"}, \text{"delimited"}, 6)$

$$\text{rows}(Maxwell) = 119 \quad \text{cols}(Maxwell) = 11$$

Enter resistance and inductance units used in the data file:

$$R_{unit} := \Omega$$

$$L_{unit} := 10^{-9} \cdot H$$

Determine the number of windings.

$$Windings := \frac{\text{cols}(Maxwell) - 3}{2} = 4$$

Determine the number of row per frequency.

$$RowsPerFreq := Windings + 3 = 7$$

Determine the number of frequencies.
(This should be an integer.)

$$N_{freq} := \frac{\text{rows}(Maxwell)}{RowsPerFreq} - 1 = 16.00$$

Counter variable for the frequency sweep, not including the initial low-frequency simulation.

$$f := 1 \dots N_{freq}$$

Extract the frequencies used in the frequency sweep.

$$freq := \left\| \begin{array}{l} \text{for } f \in 1 \dots N_{freq} \\ \quad \left\| freq_f \leftarrow (Maxwell)_{f \cdot RowsPerFreq + 1, 1} \right\| \\ \quad freq \cdot H_z \end{array} \right\|$$

Separate the data used in the frequency sweep from the initial low-frequency simulation.

$$Sweep := \text{submatrix}(Maxwell, RowsPerFreq, \text{rows}(Maxwell), 4, \text{cols}(Maxwell))$$

Extract the resistance and inductance data into an array of matrices.

```

RLF := || for f ∈ 1 .. N_freq
|| || StartRow ← 5 + (f - 1) • RowsPerFreq
|| || StopRow ← StartRow + Windings - 1
|| || RL ← submatrix (Sweep, StartRow, StopRow, 1, 2 • Windings)
|| || RL
||

```

Separate the resistance and inductance data out of RLF into arrays of resistance and inductance matrices.

```

RF := || for f ∈ 1 .. N_freq
|| || RL ← RLF_f
|| || for Row ∈ 1 .. Windings
|| || || for Col ∈ 1 .. Windings
|| || || || R_Row, Col ← RL_Row, 2 • (Col - 1) + 1
|| || || R
|| || RF_f ← R
|| || RF • Runit
||

```

```

LF := || for f ∈ 1 .. N_freq
|| || RL ← RLF_f
|| || for Row ∈ 1 .. Windings
|| || || for Col ∈ 1 .. Windings
|| || || || L_Row, Col ← RL_Row, 2 • Col
|| || || L
|| || LF_f ← L
|| || LF • Lunit
||

```

Create arrays for the resistance and inductance data.

$$\begin{aligned}
 R11_f &:= (RF_f)_{1,1} & R33_f &:= (RF_f)_{3,3} & R12_f &:= (RF_f)_{1,2} & R14_f &:= (RF_f)_{1,4} & R24_f &:= (RF_f)_{2,4} \\
 R22_f &:= (RF_f)_{2,2} & R44_f &:= (RF_f)_{4,4} & R13_f &:= (RF_f)_{1,3} & R23_f &:= (RF_f)_{2,3} & R34_f &:= (RF_f)_{3,4} \\
 L11_f &:= (LF_f)_{1,1} & L33_f &:= (LF_f)_{3,3} & L12_f &:= (LF_f)_{1,2} & L14_f &:= (LF_f)_{1,4} & L24_f &:= (LF_f)_{2,4} \\
 L22_f &:= (LF_f)_{2,2} & L44_f &:= (LF_f)_{4,4} & L13_f &:= (LF_f)_{1,3} & L23_f &:= (LF_f)_{2,3} & L34_f &:= (LF_f)_{3,4}
 \end{aligned}$$

Counter variables and unit definitions.

$$n := 1 \dots 4 \quad o := 1 \dots 4 \quad m\Omega := \frac{\Omega}{1000} \quad nH := H \cdot 10^{-9}$$

A 1 Hz simulation is used to approximate the dc characteristics.

$$freq_min := Maxwell_{1,1} \cdot Hz = 1 \text{ Hz}$$

Separate the data for the initial low-frequency simulation.

$$RL0 := \text{submatrix}(Maxwell, 4, RowsPerFreq, 4, \text{cols}(Maxwell))$$

$$R_{\theta_{n,o}} := RL0_{n,2 \cdot o - 1} \cdot Runit \quad L_{\theta_{n,o}} := RL0_{n,2 \cdot o} \cdot Lunit$$

The diagonal entries will be used for the dc values of the winding resistances.

$$R_{\theta} = \begin{bmatrix} 0.0091 & 3.1879 \cdot 10^{-9} & 3.1406 \cdot 10^{-9} & 9.3019 \cdot 10^{-9} \\ 3.1879 \cdot 10^{-9} & 0.0016 & 1.0364 \cdot 10^{-9} & 3.0759 \cdot 10^{-9} \\ 3.1406 \cdot 10^{-9} & 1.0364 \cdot 10^{-9} & 0.0018 & 3.0606 \cdot 10^{-9} \\ 9.3019 \cdot 10^{-9} & 3.0759 \cdot 10^{-9} & 3.0606 \cdot 10^{-9} & 0.0142 \end{bmatrix} \Omega$$

The diagonal entries will be used for the base values of the winding inductances. The winding losses cause the inductances to slightly decrease with frequency.

$$L_{\theta} = \begin{bmatrix} 0.1942 & 0.0646 & 0.0644 & 0.1927 \\ 0.0646 & 0.0216 & 0.0215 & 0.0644 \\ 0.0644 & 0.0215 & 0.0216 & 0.0645 \\ 0.1927 & 0.0644 & 0.0645 & 0.1940 \end{bmatrix} mH$$

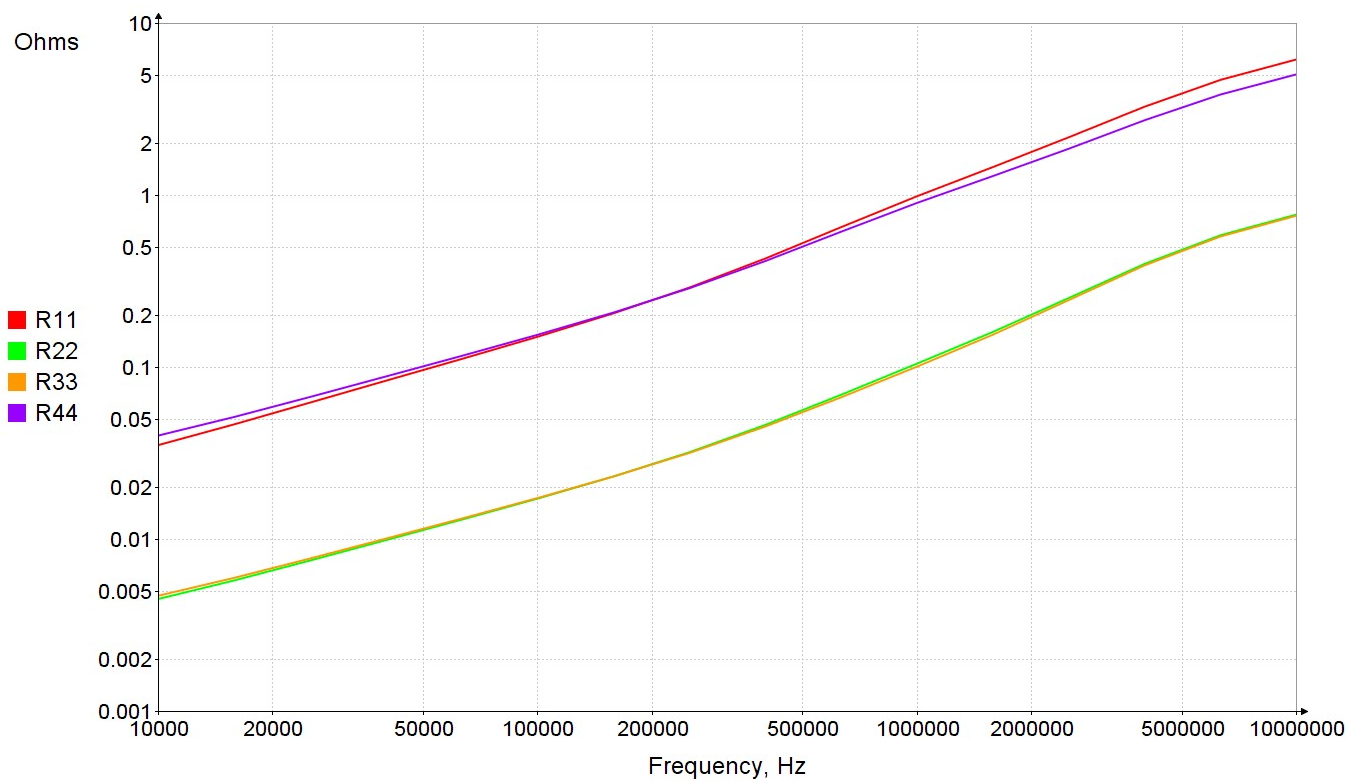


Fig. 2. Simulated self resistances.

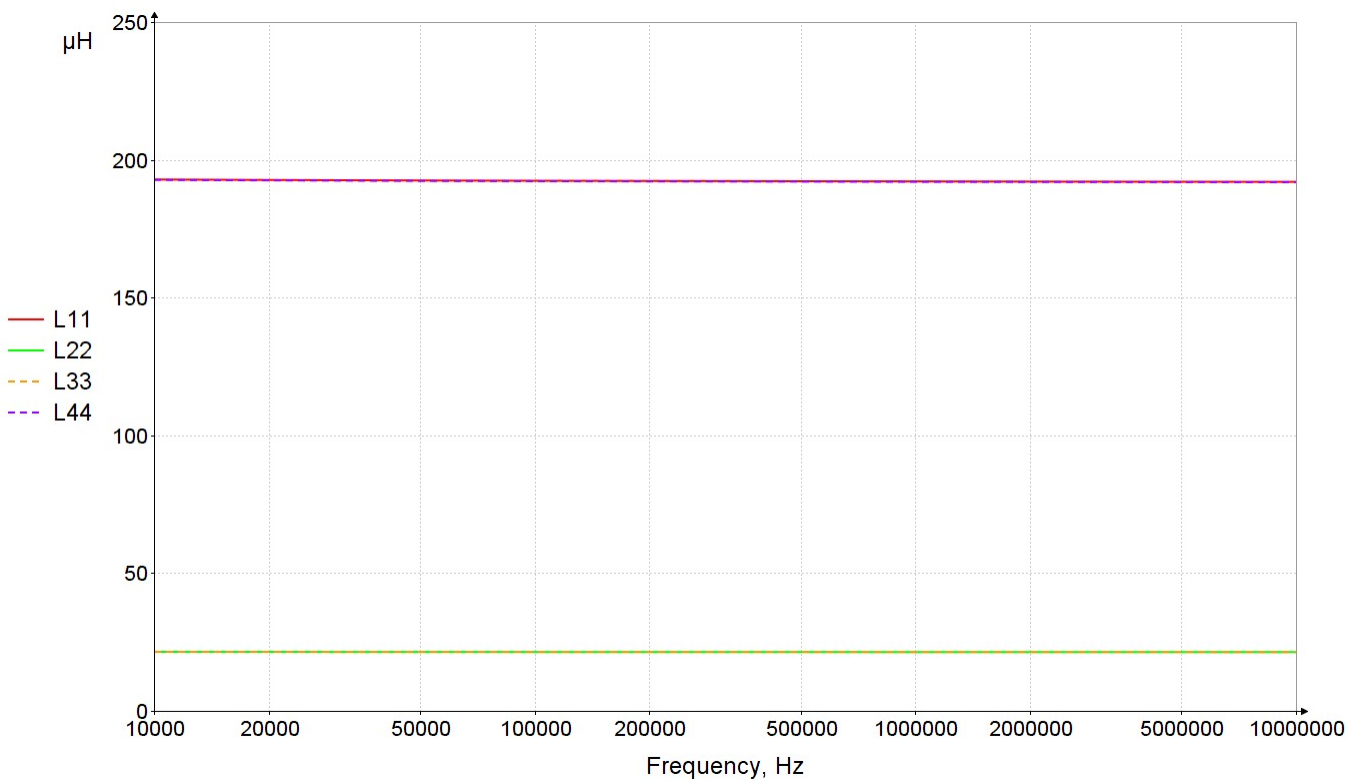


Fig. 3. Simulated self inductances.

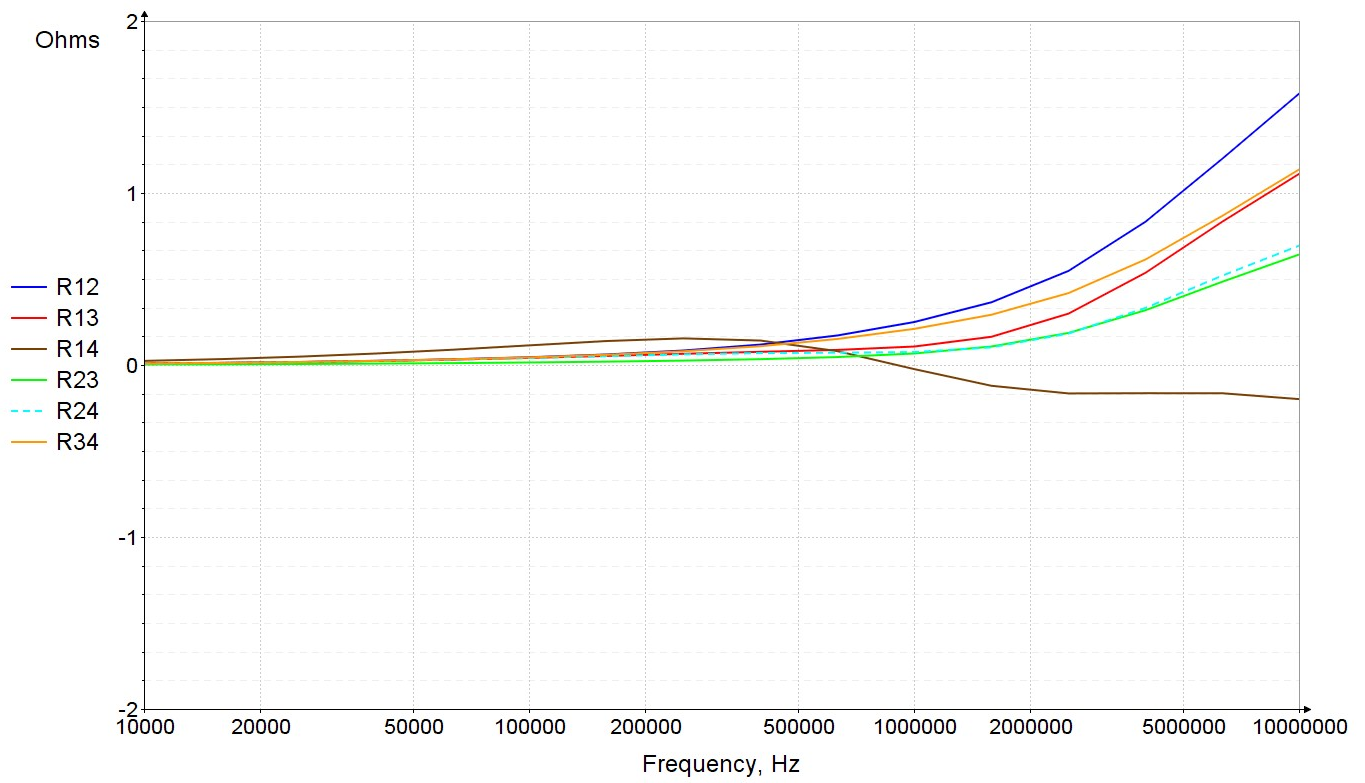


Fig. 4. Simulated mutual resistances.

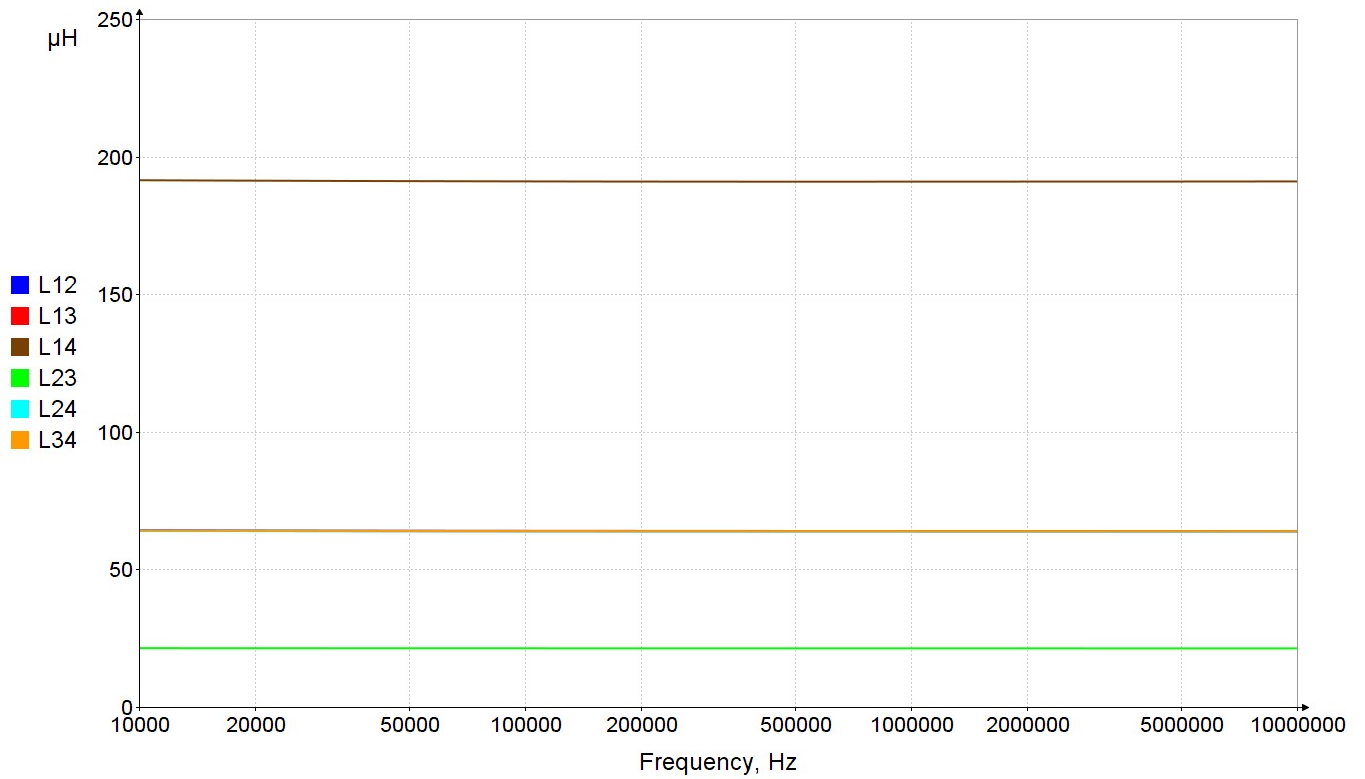


Fig. 5. Simulated mutual inductances.

L12, L13, L24 and L34 are nearly equal.

The imported simulation data is made available for subsequent calculation through functions that are indexed by the frequency of the matrix data.

$$RF(f) := \begin{bmatrix} R11_f \\ R22_f \\ R33_f \\ R44_f \\ R12_f \\ R13_f \\ R14_f \\ R23_f \\ R24_f \\ R34_f \end{bmatrix} \quad LF(f) := \begin{bmatrix} L11_f \\ L22_f \\ L33_f \\ L44_f \\ L12_f \\ L13_f \\ L14_f \\ L23_f \\ L24_f \\ L34_f \end{bmatrix}$$

Radian frequencies $\omega_f := 2 \cdot \pi \cdot freq_f$

We begin the process of modeling the transformer by defining the voltages and currents as shown in Fig. 6.

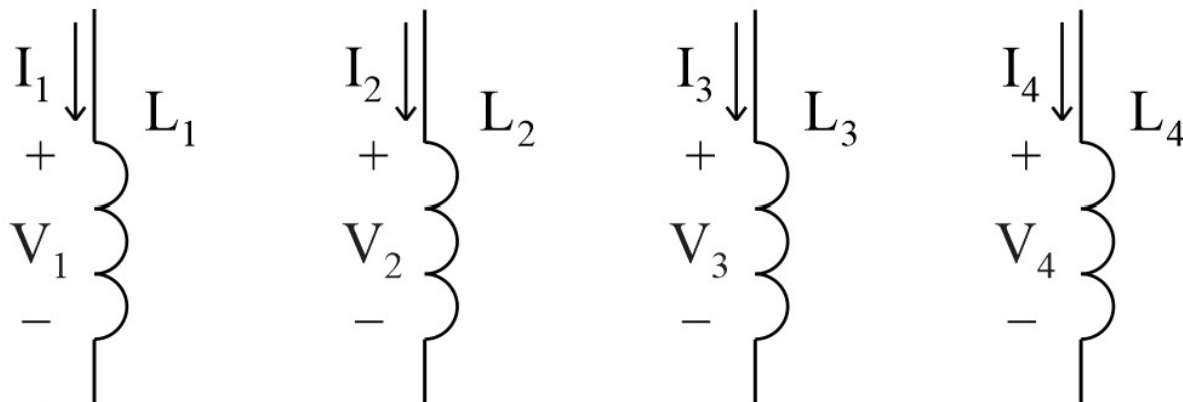


Fig. 6. Voltages and currents

As with any four-port network, the transformer voltages and currents can be described in the frequency domain in terms of self and mutual impedances.

$$V_1 = Z_{11} \cdot I_1 + Z_{12} \cdot I_2 + Z_{13} \cdot I_3 + Z_{14} \cdot I_4 \quad (1)$$

$$V_2 = Z_{21} \cdot I_1 + Z_{22} \cdot I_2 + Z_{23} \cdot I_3 + Z_{24} \cdot I_4 \quad (2)$$

$$V_3 = Z_{31} \cdot I_1 + Z_{32} \cdot I_2 + Z_{33} \cdot I_3 + Z_{34} \cdot I_4 \quad (3)$$

$$V_4 = Z_{41} \cdot I_1 + Z_{42} \cdot I_2 + Z_{43} \cdot I_3 + Z_{44} \cdot I_4 \quad (4)$$

Compute the self impedances from the simulated resistance and inductance values.

$$Z_{11} := \overrightarrow{(R_{11} + 1j \cdot \omega \cdot L_{11})} \quad Z_{22} := \overrightarrow{(R_{22} + 1j \cdot \omega \cdot L_{22})} \quad Z_{33} := \overrightarrow{(R_{33} + 1j \cdot \omega \cdot L_{33})} \quad Z_{44} := \overrightarrow{(R_{44} + 1j \cdot \omega \cdot L_{44})}$$

Compute the mutual impedances from the simulated leakage resistance and inductance values.

$$Z_{12} := \overrightarrow{(R_{12} + 1j \cdot \omega \cdot L_{12})} \quad Z_{13} := \overrightarrow{(R_{13} + 1j \cdot \omega \cdot L_{13})} \quad Z_{14} := \overrightarrow{(R_{14} + 1j \cdot \omega \cdot L_{14})} \quad Z_{23} := \overrightarrow{(R_{23} + 1j \cdot \omega \cdot L_{23})}$$

$$Z_{24} := \overrightarrow{(R_{24} + 1j \cdot \omega \cdot L_{24})} \quad Z_{34} := \overrightarrow{(R_{34} + 1j \cdot \omega \cdot L_{34})}$$

Formula for leakage impedances in terms of the self and mutual impedances.

Measured winding: m
Shorted winding: n

$$Z_{leak_mn} = Z_{mm} - \frac{Z_{mn}^2}{Z_{nn}} \quad (5)$$

Compute the leakage impedances.

$$Z_{leak12} := \overrightarrow{\left(Z_{11} - \frac{Z_{12}^2}{Z_{22}} \right)} \quad Z_{leak13} := \overrightarrow{\left(Z_{11} - \frac{Z_{13}^2}{Z_{33}} \right)} \quad Z_{leak14} := \overrightarrow{\left(Z_{11} - \frac{Z_{14}^2}{Z_{44}} \right)}$$

$$Z_{leak23} := \overrightarrow{\left(Z_{22} - \frac{Z_{23}^2}{Z_{33}} \right)} \quad Z_{leak24} := \overrightarrow{\left(Z_{22} - \frac{Z_{24}^2}{Z_{44}} \right)} \quad Z_{leak34} := \overrightarrow{\left(Z_{33} - \frac{Z_{34}^2}{Z_{44}} \right)}$$

Compute the leakage resistances and inductances from the leakage impedances.

$$\begin{aligned}
 R_{leak12} &:= \operatorname{Re}(Z_{leak12}) & R_{leak13} &:= \operatorname{Re}(Z_{leak13}) & R_{leak14} &:= \operatorname{Re}(Z_{leak14}) & R_{leak23} &:= \operatorname{Re}(Z_{leak23}) \\
 R_{leak24} &:= \operatorname{Re}(Z_{leak24}) & R_{leak34} &:= \operatorname{Re}(Z_{leak34}) \\
 L_{leak12} &:= \frac{\operatorname{Im}(Z_{leak12})}{\omega} & L_{leak13} &:= \frac{\operatorname{Im}(Z_{leak13})}{\omega} & L_{leak14} &:= \frac{\operatorname{Im}(Z_{leak14})}{\omega} & L_{leak23} &:= \frac{\operatorname{Im}(Z_{leak23})}{\omega} \\
 L_{leak24} &:= \frac{\operatorname{Im}(Z_{leak24})}{\omega} & L_{leak34} &:= \frac{\operatorname{Im}(Z_{leak34})}{\omega}
 \end{aligned}$$

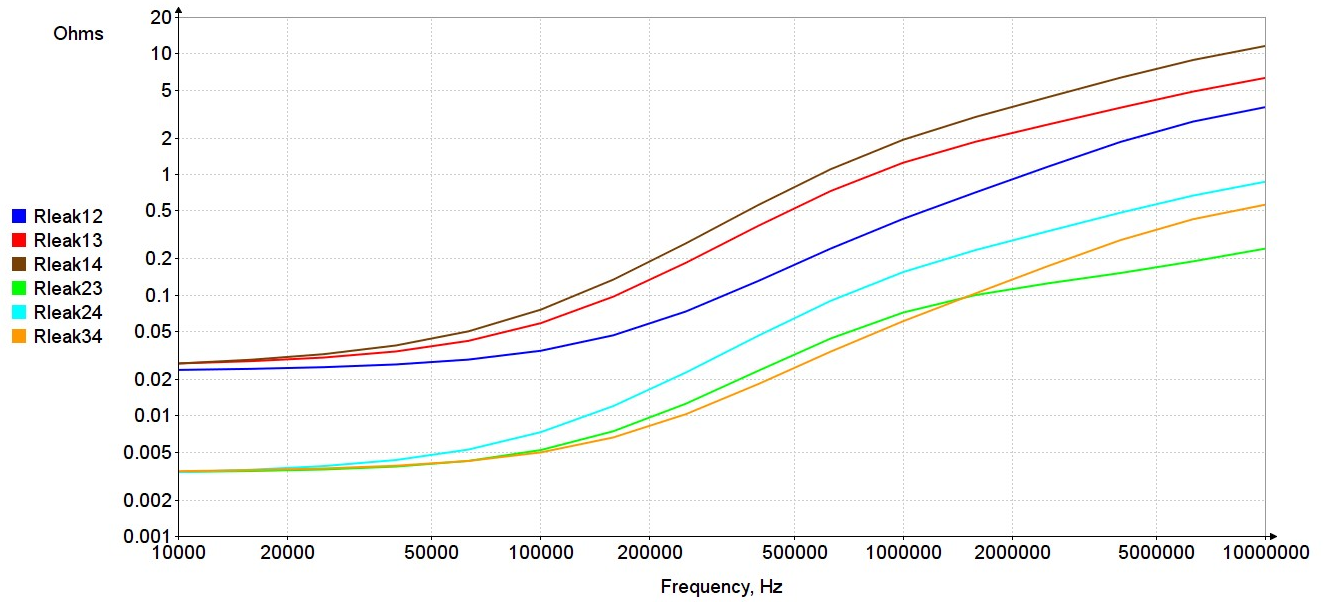


Fig. 7. Leakage resistances.

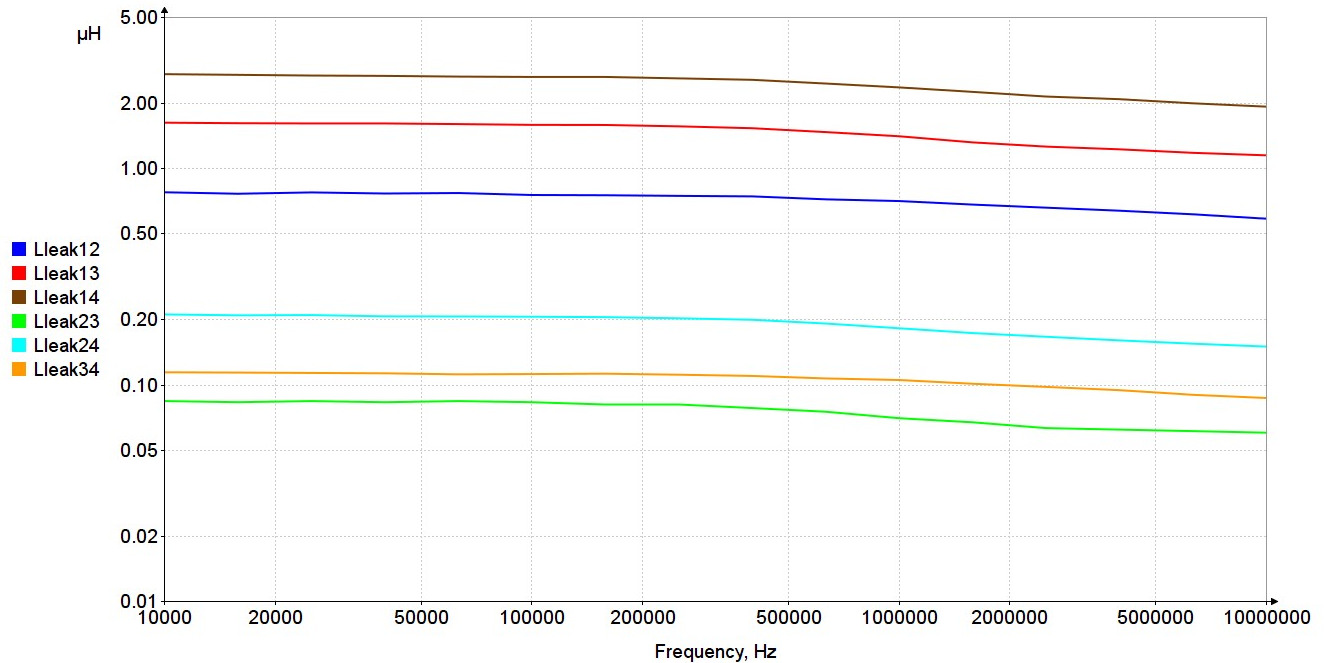


Fig. 8. Leakage inductances.

Mutual inductance
couplings

$$k_{12} := \frac{\overrightarrow{L12}}{\sqrt{L11 \cdot L22}}$$

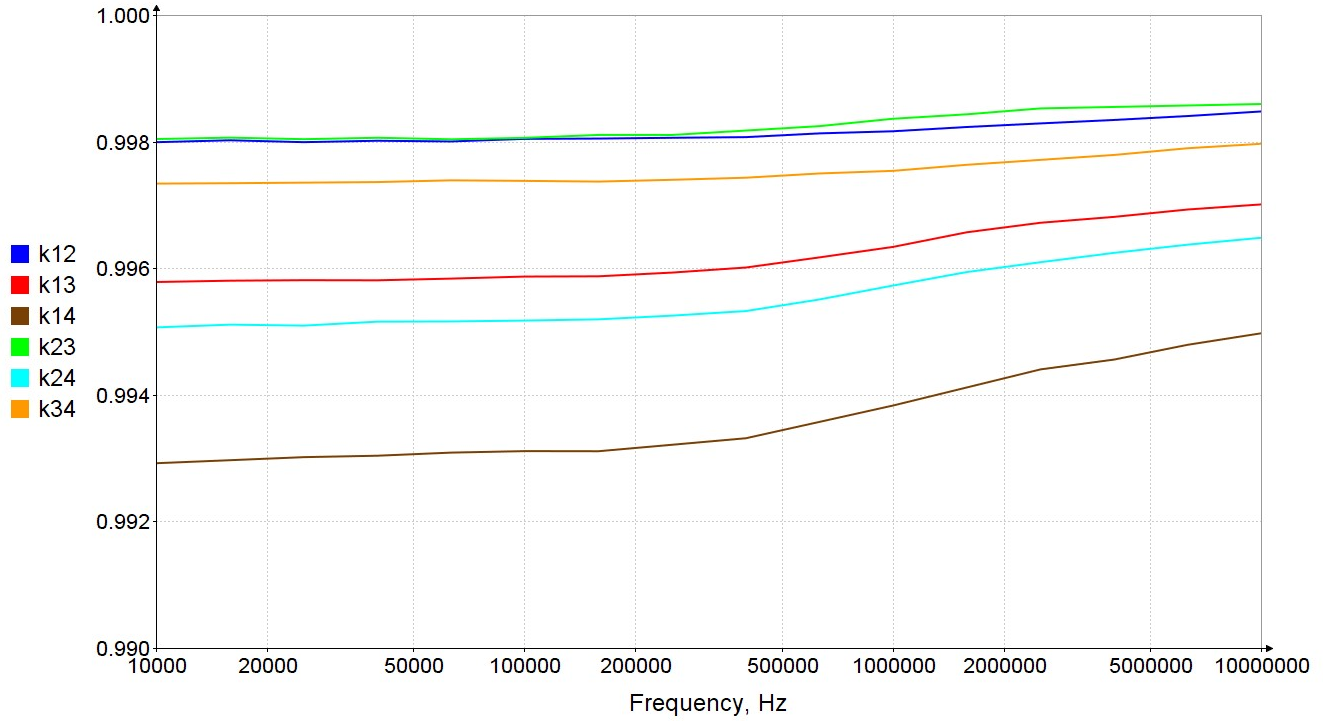
$$k_{13} := \frac{\overrightarrow{L13}}{\sqrt{L11 \cdot L33}}$$

$$k_{14} := \frac{\overrightarrow{L14}}{\sqrt{L11 \cdot L44}}$$

$$k_{23} := \frac{\overrightarrow{L23}}{\sqrt{L22 \cdot L33}}$$

$$k_{24} := \frac{\overrightarrow{L24}}{\sqrt{L22 \cdot L44}}$$

$$k_{34} := \frac{\overrightarrow{L34}}{\sqrt{L33 \cdot L44}}$$



Mutual resistance
couplings

$$kr_{12} := \frac{\overrightarrow{R12}}{\sqrt{R11 \cdot R22}}$$

$$kr_{13} := \frac{\overrightarrow{R13}}{\sqrt{R11 \cdot R33}}$$

$$kr_{14} := \frac{\overrightarrow{R14}}{\sqrt{R11 \cdot R44}}$$

$$kr_{23} := \frac{\overrightarrow{R23}}{\sqrt{R22 \cdot R33}}$$

$$kr_{24} := \frac{\overrightarrow{R24}}{\sqrt{R22 \cdot R44}}$$

$$kr_{34} := \frac{\overrightarrow{R34}}{\sqrt{R33 \cdot R44}}$$

Mutual Resistance Function

$$KR(f) := \begin{bmatrix} kr_{12}_f \\ kr_{13}_f \\ kr_{14}_f \\ kr_{23}_f \\ kr_{24}_f \\ kr_{34}_f \end{bmatrix}$$

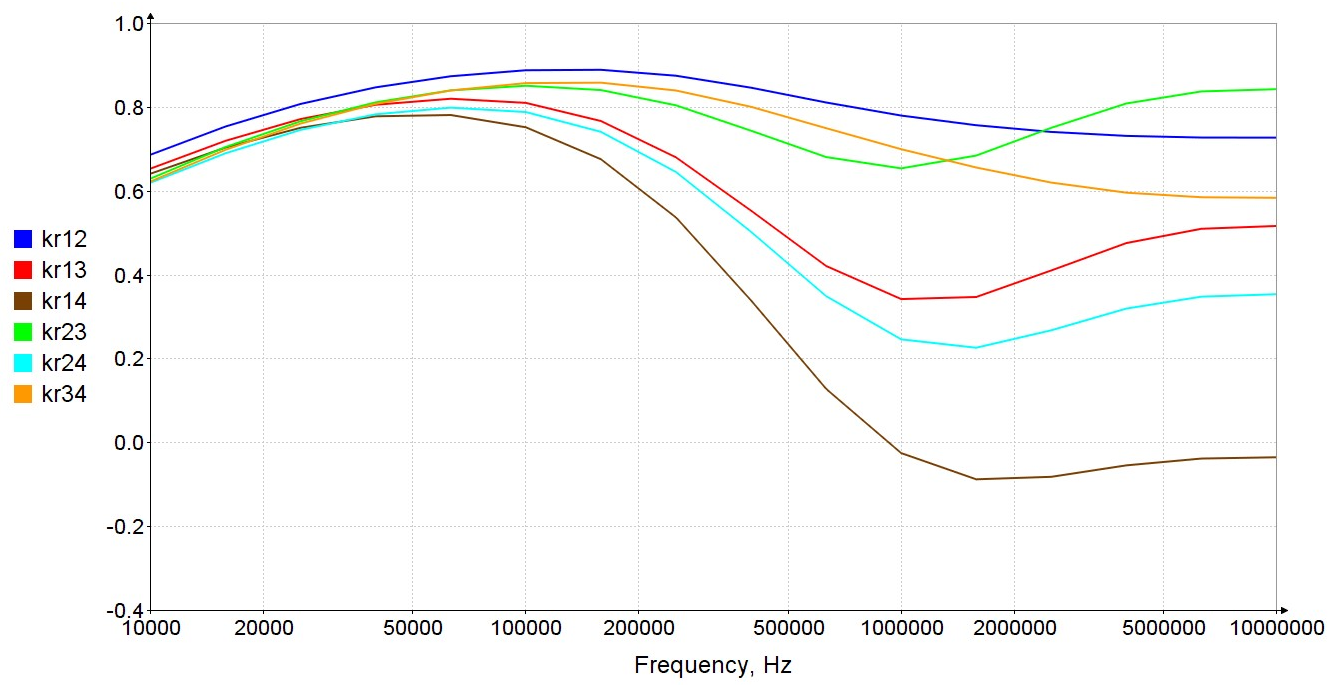


Fig. 9. Mutual Resistance Couplings.

N1 = 12 Turns, N2 = 4 Turns, N3 = 4 Turns, N4 = 12 Turns

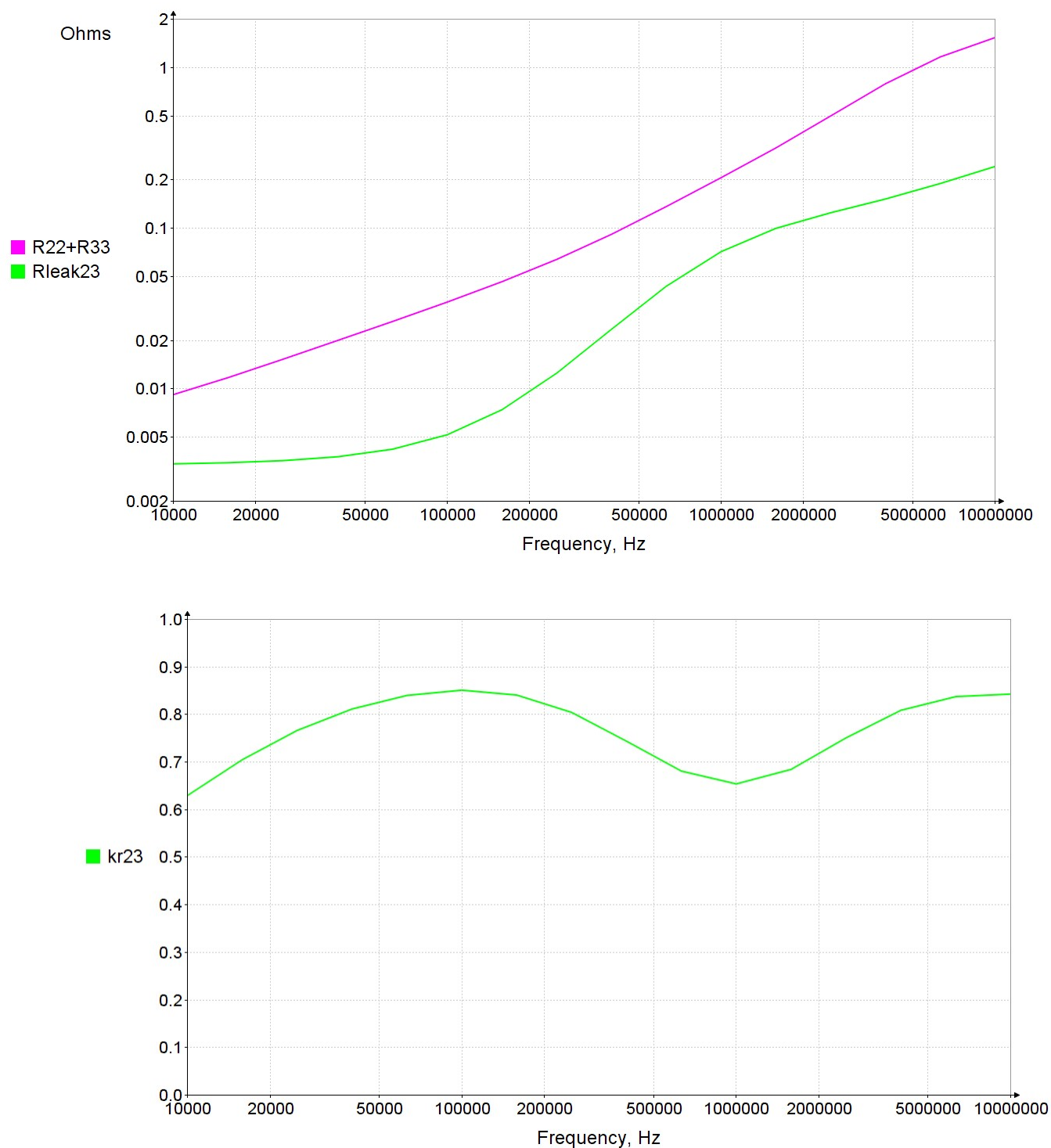


Fig. 10. Comparison between sum of self and reflected self resistances for high positive mutual resistance.

There is a significant reduction of the ac resistance due to the mutual resistance between these adjacent windings.

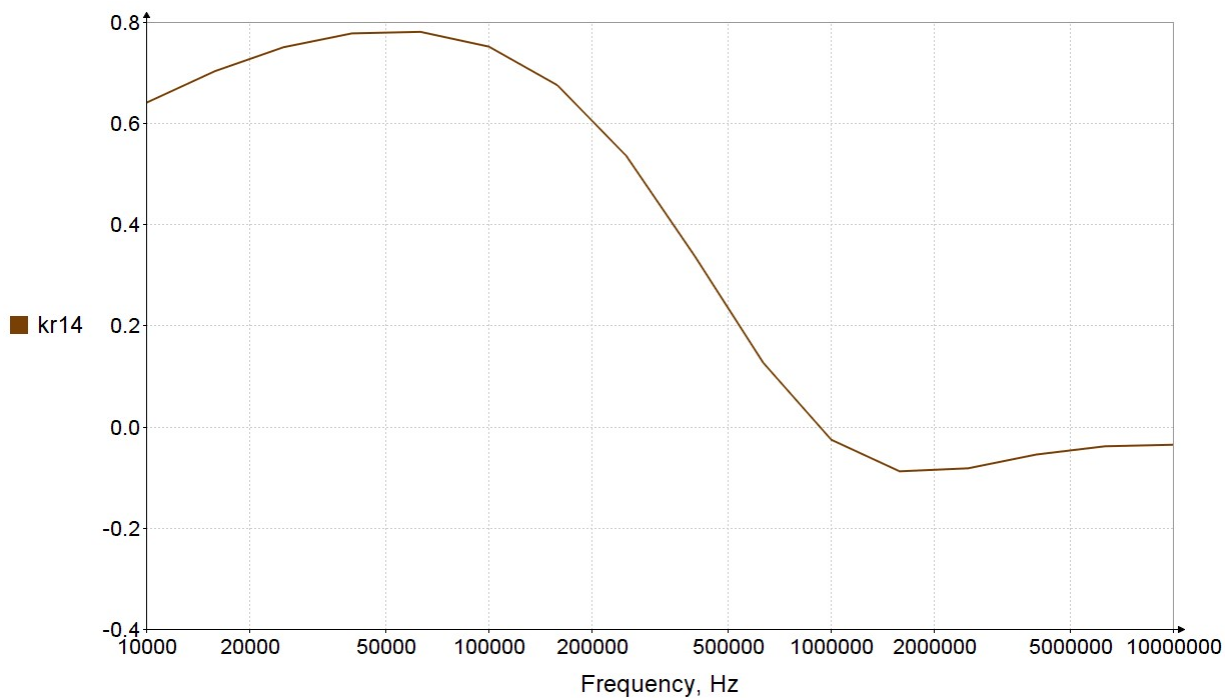
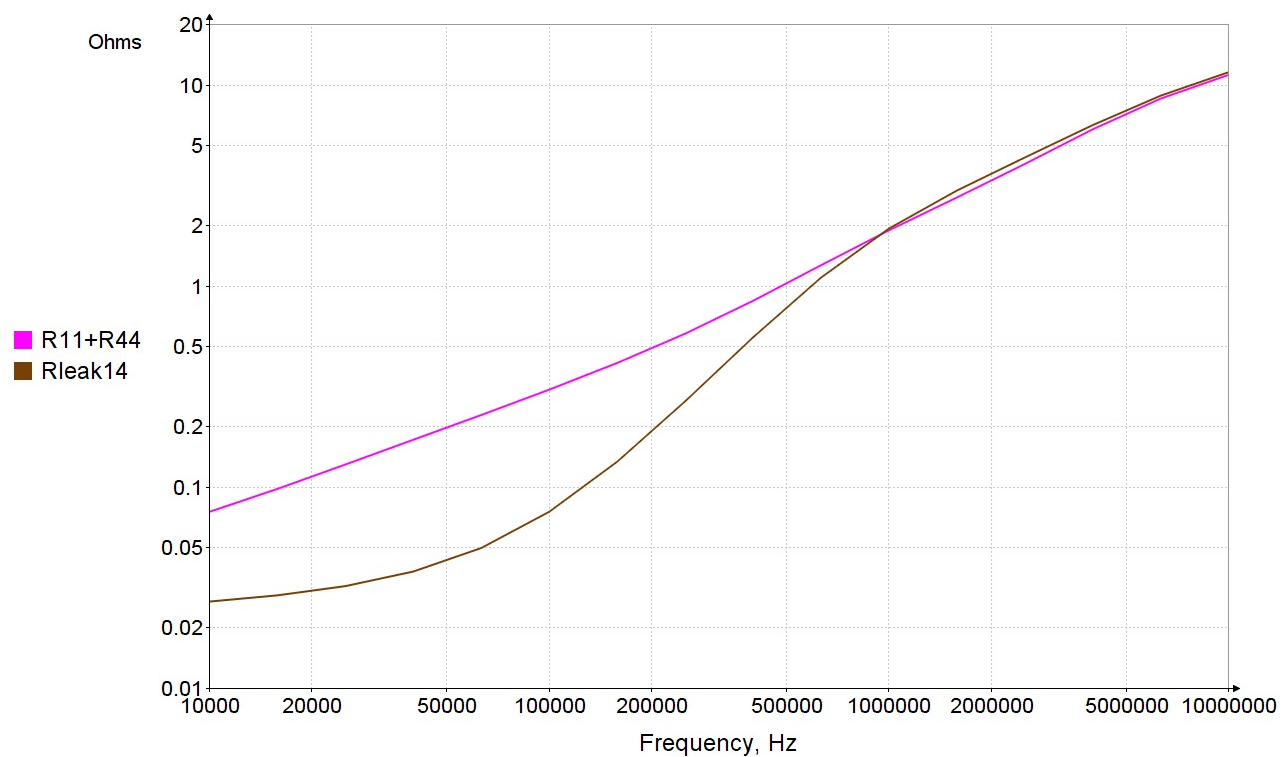


Fig. 11. Comparison between sum of self and reflected self resistances for lower mutual resistance.

These coils are not adjacent, and mutual resistance actually becomes negative above 40 kHz, which causes the leakage resistance to be greater than the sum of the resistance of winding 1 plus the reflected resistance of winding 4.

The impedance matrix description of the transformer can be approximated with the circuit model shown below in Fig. 12 as explained in [1]. For each winding, there is a resistor representing the dc resistance of that winding and a main inductor representing the maximum low-frequency inductance for that winding. The main inductor and the dc resistance for each winding are connected in series between the electrical terminals of that winding. There is also a set of auxiliary circuits for each winding that is shown in a row to the left of the winding. Each auxiliary circuit consists of an auxiliary inductor that is connected in parallel with an auxiliary resistor. The bottom terminals of all of the inductors in each set are connected together to prevent floating nodes, which are not allowed in circuit simulators.

The schematic diagram shows two auxiliary circuits for each winding, but the model could be extended to include more auxiliary circuits. Increasing the number of auxiliary circuits increases the frequency range over which the skin effect can be modeled.

The main inductors are coupled to each other and to each of the auxiliary inductors. The auxiliary inductors are not coupled to each other. It is, of course, impossible to construct a magnetic device in which a set of uncoupled windings are all coupled some other winding. This arrangement is useful as a model, however, and it is possible to describe it mathematically, and to model it in circuit simulators.

The model has one more degree of freedom than is necessary for each auxiliary inductors, so the inductances of the auxiliary inductors in each set are assigned a value equal to the inductance of the main winding associated with that set.

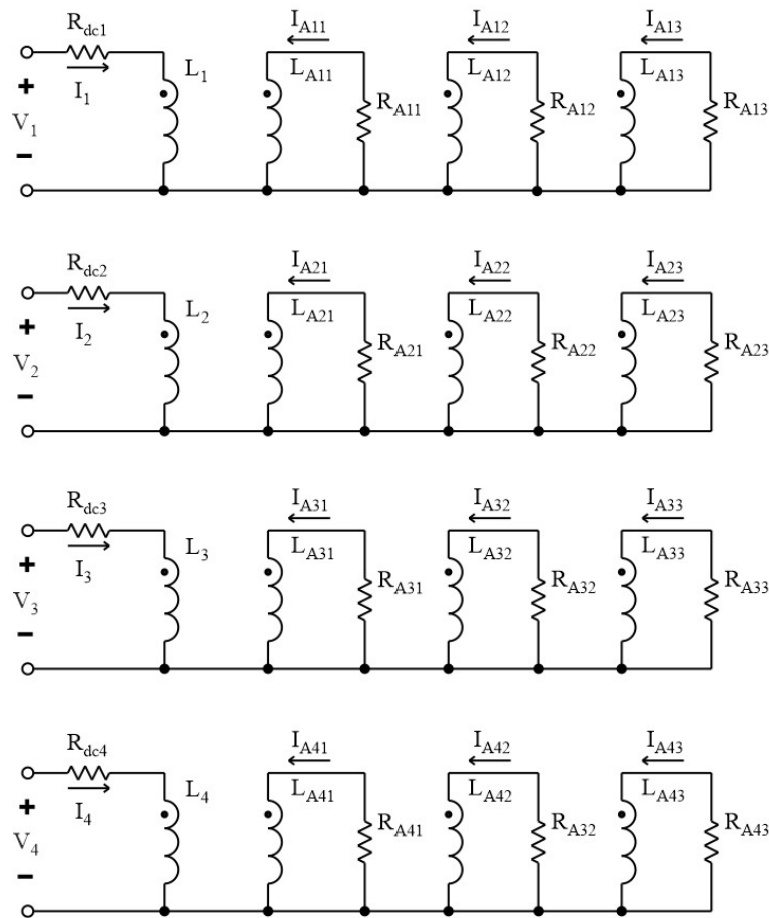


Figure 12. Schematic diagram of transformer circuit model.

We now define several variables and matrices that will be used in an equation that describes the circuit of Fig. 12.

The total number of auxiliary circuits for each winding is designated as r , which is 3 in Fig. 12. The counter variable κ indicates the κ th auxiliary circuit, and it ranges from 1 to r .

$$N := 4 \qquad r := 3 \qquad N_{aux} := N \cdot r = 12 \qquad Nk := N^2 \cdot r = 48$$

The mutual inductance between L_1 and L_2 is designated M_{12} .

The elements of M are calculated as shown below.

$$\begin{array}{|l} a \leftarrow 1 \\ Cols \leftarrow N_{aux} \\ \text{for } row \in 1 \dots N \\ \quad \text{for } col \in 1 \dots Cols \\ \quad \quad M_{row, col} \leftarrow k_{A_a} \cdot \sqrt{L_{A_{col}} \cdot L_{b_{row, row}}} \\ \quad \quad a \leftarrow a + 1 \\ M \end{array}$$

Define a matrix of the main self and mutual inductances calculated with the initial low-frequency simulation, which was selected to be low enough that the auxiliary circuits have little effect at that frequency.

$$Lb := L_0 \quad freq_min = 1 \text{ Hz}$$

$$Lb = \begin{bmatrix} 194.2 & 64.607 & 64.449 & 192.68 \\ 64.607 & 21.581 & 21.535 & 64.376 \\ 64.449 & 21.535 & 21.575 & 64.519 \\ 192.68 & 64.376 & 64.519 & 193.99 \end{bmatrix} \mu H$$

Compute the coupling coefficient matrix corresponding to Lb to get an idea of the couplings among the wires. Kb is the coupling coefficient between the main windings.

$$Kb := \begin{bmatrix} 1 & \frac{Lb_{1,2}}{\sqrt{Lb_{1,1} \cdot Lb_{2,2}}} & \frac{Lb_{1,3}}{\sqrt{Lb_{1,1} \cdot Lb_{3,3}}} & \frac{Lb_{1,4}}{\sqrt{Lb_{1,1} \cdot Lb_{4,4}}} \\ \frac{Lb_{1,2}}{\sqrt{Lb_{1,1} \cdot Lb_{2,2}}} & 1 & \frac{Lb_{2,3}}{\sqrt{Lb_{2,2} \cdot Lb_{3,3}}} & \frac{Lb_{2,4}}{\sqrt{Lb_{2,2} \cdot Lb_{4,4}}} \\ \frac{Lb_{1,3}}{\sqrt{Lb_{1,1} \cdot Lb_{3,3}}} & \frac{Lb_{2,3}}{\sqrt{Lb_{2,2} \cdot Lb_{3,3}}} & 1 & \frac{Lb_{3,4}}{\sqrt{Lb_{3,3} \cdot Lb_{4,4}}} \\ \frac{Lb_{1,4}}{\sqrt{Lb_{1,1} \cdot Lb_{4,4}}} & \frac{Lb_{2,4}}{\sqrt{Lb_{2,2} \cdot Lb_{4,4}}} & \frac{Lb_{3,4}}{\sqrt{Lb_{3,3} \cdot Lb_{4,4}}} & 1 \end{bmatrix}$$

$$Kb = \begin{bmatrix} 1.0000 & 0.9980 & 0.9957 & 0.9927 \\ 0.9980 & 1.0000 & 0.9980 & 0.9949 \\ 0.9957 & 0.9980 & 1.0000 & 0.9973 \\ 0.9927 & 0.9949 & 0.9973 & 1.0000 \end{bmatrix}$$

All of the eigenvalues must be positive to have a stable model [2].

$$\text{eigenvals}(Kb) = \begin{bmatrix} 3.988 \\ 0.008 \\ 0.002 \\ 0.001 \end{bmatrix}$$

The value of each auxiliary inductor is set equal to the value of the corresponding main winding.

$$L_A := \begin{array}{|l} \text{row} \leftarrow 0 \\ \text{for } n \in 1 \dots N \\ \quad \text{for } a \in 1 \dots r \\ \quad \quad \text{row} \leftarrow \text{row} + 1 \\ \quad \quad L_{\text{row}} \leftarrow Lb_{n,n} \\ \quad \quad L \end{array}$$

R_A contains the initial guess values of the auxiliary resistors for solve block.

k_A contains the initial guess values of the coupling coefficients between the auxiliary circuits and the main windings.

$$R_A := \begin{bmatrix} 10 \\ 100 \\ 1000 \\ 10 \\ 100 \\ 1000 \\ 10 \\ 100 \\ 1000 \\ 10 \\ 100 \\ 1000 \end{bmatrix} \cdot \Omega$$

$$k_A := \begin{array}{|l} \text{for } n \in 1 \dots Nk \\ \quad K_n \leftarrow 0.001 \\ \quad K \end{array}$$

$$M(k_A) := \begin{array}{|l} a \leftarrow 1 \\ Cols \leftarrow N_{aux} \\ \text{for } row \in 1 \dots N \\ \quad \text{for } col \in 1 \dots Cols \\ \quad \quad M_{row,col} \leftarrow k_{A_a} \cdot \sqrt{L_{A_{col}} \cdot Lb_{row,row}} \\ \quad \quad a \leftarrow a + 1 \\ \quad M \end{array}$$

$$Rb := \begin{bmatrix} R_{0_{1,1}} & 0 & 0 & 0 \\ 0 & R_{0_{2,2}} & 0 & 0 \\ 0 & 0 & R_{0_{3,3}} & 0 \\ 0 & 0 & 0 & R_{0_{4,4}} \end{bmatrix}$$

$$Rb = \begin{bmatrix} 9.085 & 0 & 0 & 0 \\ 0 & 1.557 & 0 & 0 \\ 0 & 0 & 1.766 & 0 \\ 0 & 0 & 0 & 14.18 \end{bmatrix} m\Omega$$

Functions to define the G and B matrices described in [1]. G and B are needed to find the impedances of the transformer equivalent circuit shown in Fig. 12.

$$G(f, L_A, R_A) := \left\| \begin{array}{l} G_A \leftarrow \left(\frac{R_A}{R_A^2 + (\omega_f)^2 \cdot L_A^2} \right) \\ X \leftarrow \frac{\text{identity}(Naux)}{\Omega} \\ \text{for } n \in 1 \dots Naux \\ \quad \left\| X_{n,n} \leftarrow G_{A_n} \right\| \\ X \end{array} \right\|$$

$$B(f, L_A, R_A) := \left\| \begin{array}{l} B_A \leftarrow \left(\frac{L_A}{R_A^2 + (\omega_f)^2 \cdot L_A^2} \right) \\ X \leftarrow \text{identity}(Naux) \cdot \frac{s}{\Omega} \\ \text{for } n \in 1 \dots Naux \\ \quad \left\| X_{n,n} \leftarrow B_{A_n} \right\| \\ X \end{array} \right\|$$

$$\text{rows}(G(1, L_A, R_A)) = 12$$

$$\text{cols}(G(1, L_A, R_A)) = 12$$

$$\text{rows}(B(1, L_A, R_A)) = 12$$

$$\text{cols}(B(1, L_A, R_A)) = 12$$

Function to calculate the equivalent circuit self and mutual resistances.

$$R_{eq}(R_A, k_A, f) := \left\| \begin{array}{l} R \leftarrow Rb + (\omega_f)^2 \cdot M(k_A) \cdot G(f, L_A, R_A) \cdot M(k_A)^T \\ \left[\begin{array}{l} R_{1,1} \\ R_{2,2} \\ R_{3,3} \\ R_{4,4} \\ R_{1,2} \\ R_{1,3} \\ R_{1,4} \\ R_{2,3} \\ R_{2,4} \\ R_{3,4} \end{array} \right] \end{array} \right\|$$

$$\text{rows}(R_{eq}(R_A, k_A, 1)) = 10$$

$$\text{cols}(R_{eq}(R_A, k_A, 1)) = 1$$

LI

Function to calculate self and mutual inductances of the the equivalent circuit

$$L_{eq}(R_A, k_A, f) := \left\| \begin{array}{l} L \leftarrow Lb - (\omega_f)^2 \cdot M(k_A) \cdot B(f, L_A, R_A) \cdot M(k_A)^T \\ \begin{bmatrix} L_{1,1} \\ L_{2,2} \\ L_{3,3} \\ L_{4,4} \\ L_{1,2} \\ L_{1,3} \\ L_{1,4} \\ L_{2,3} \\ L_{2,4} \\ L_{3,4} \end{bmatrix} \end{array} \right\|$$

Function to calculate the equivalent circuit self and mutual impedances.

$$Z_{eq}(R_A, k_A, f) := R_{eq}(R_A, k_A, f) + 1j \cdot \omega_f \cdot L_{eq}(R_A, k_A, f)$$

Functions to calculate leakage impedances based on (5).

$$Z_{leak_mn} = Z_{mm} - \frac{Z_{mn}^2}{Z_{nn}} \quad (5)$$

$$Rleak12EQ(R_A, k_A, f) := \text{Re} \left(Z_{eq}(R_A, k_A, f)_1 - \frac{(Z_{eq}(R_A, k_A, f)_5)^2}{Z_{eq}(R_A, k_A, f)_2} \right)$$

$$Rleak13EQ(R_A, k_A, f) := \text{Re} \left(Z_{eq}(R_A, k_A, f)_1 - \frac{(Z_{eq}(R_A, k_A, f)_6)^2}{Z_{eq}(R_A, k_A, f)_3} \right)$$

$$Rleak14EQ(R_A, k_A, f) := \text{Re} \left(Z_{eq}(R_A, k_A, f)_1 - \frac{(Z_{eq}(R_A, k_A, f)_7)^2}{Z_{eq}(R_A, k_A, f)_4} \right)$$

$$Rleak23EQ \langle R_A, k_A, f \rangle := \text{Re} \left(Z_{eq} \langle R_A, k_A, f \rangle_2 - \frac{\left(Z_{eq} \langle R_A, k_A, f \rangle_8 \right)^2}{Z_{eq} \langle R_A, k_A, f \rangle_3} \right)$$

$$Rleak24EQ \langle R_A, k_A, f \rangle := \text{Re} \left(Z_{eq} \langle R_A, k_A, f \rangle_2 - \frac{\left(Z_{eq} \langle R_A, k_A, f \rangle_9 \right)^2}{Z_{eq} \langle R_A, k_A, f \rangle_4} \right)$$

$$Rleak34EQ \langle R_A, k_A, f \rangle := \text{Re} \left(Z_{eq} \langle R_A, k_A, f \rangle_3 - \frac{\left(Z_{eq} \langle R_A, k_A, f \rangle_{10} \right)^2}{Z_{eq} \langle R_A, k_A, f \rangle_4} \right)$$

$$Lleak12EQ \langle R_A, k_A, f \rangle := \frac{1}{\omega_f} \cdot \text{Im} \left(Z_{eq} \langle R_A, k_A, f \rangle_1 - \frac{\left(Z_{eq} \langle R_A, k_A, f \rangle_5 \right)^2}{Z_{eq} \langle R_A, k_A, f \rangle_2} \right)$$

$$Lleak13EQ \langle R_A, k_A, f \rangle := \frac{1}{\omega_f} \cdot \text{Im} \left(Z_{eq} \langle R_A, k_A, f \rangle_1 - \frac{\left(Z_{eq} \langle R_A, k_A, f \rangle_6 \right)^2}{Z_{eq} \langle R_A, k_A, f \rangle_3} \right)$$

$$Lleak14EQ \langle R_A, k_A, f \rangle := \frac{1}{\omega_f} \cdot \text{Im} \left(Z_{eq} \langle R_A, k_A, f \rangle_1 - \frac{\left(Z_{eq} \langle R_A, k_A, f \rangle_7 \right)^2}{Z_{eq} \langle R_A, k_A, f \rangle_4} \right)$$

$$Lleak23EQ \langle R_A, k_A, f \rangle := \frac{1}{\omega_f} \cdot \text{Im} \left(Z_{eq} \langle R_A, k_A, f \rangle_2 - \frac{\left(Z_{eq} \langle R_A, k_A, f \rangle_8 \right)^2}{Z_{eq} \langle R_A, k_A, f \rangle_3} \right)$$

$$Lleak24EQ \langle R_A, k_A, f \rangle := \frac{1}{\omega_f} \cdot \text{Im} \left(Z_{eq} \langle R_A, k_A, f \rangle_2 - \frac{\left(Z_{eq} \langle R_A, k_A, f \rangle_9 \right)^2}{Z_{eq} \langle R_A, k_A, f \rangle_4} \right)$$

$$Lleak34EQ \langle R_A, k_A, f \rangle := \frac{1}{\omega_f} \cdot \text{Im} \left(Z_{eq} \langle R_A, k_A, f \rangle_3 - \frac{\left(Z_{eq} \langle R_A, k_A, f \rangle_{10} \right)^2}{Z_{eq} \langle R_A, k_A, f \rangle_4} \right)$$

Function to calculate the mutual resistance couplings of the the equivalent circuit

$$kreq(R_A, k_A, f) := \left\| \begin{array}{l} R \leftarrow Rb + (\omega_f)^2 \cdot M(k_A) \cdot G(f, L_A, R_A) \cdot M(k_A)^T \\ \left[\begin{array}{c} R_{1,2} \\ \sqrt{R_{1,1} \cdot R_{2,2}} \\ R_{1,3} \\ \sqrt{R_{1,1} \cdot R_{3,3}} \\ R_{1,4} \\ \sqrt{R_{1,1} \cdot R_{4,4}} \\ R_{2,3} \\ \sqrt{R_{2,2} \cdot R_{3,3}} \\ R_{2,4} \\ \sqrt{R_{2,2} \cdot R_{4,4}} \\ R_{3,4} \\ \sqrt{R_{3,3} \cdot R_{4,4}} \end{array} \right] \end{array} \right\|$$

Define error functions base on mutual resistance coupling, resistance and inductance

$$Error_K(R_A, k_A, f) := \left\| \begin{array}{l} kr \leftarrow KR(f) \\ kreq(R_A, k_A, f) - kr \end{array} \right\|$$

$$Error_R(R_A, k_A, f) := \left\| \begin{array}{l} Rf \leftarrow RF(f) \\ D \leftarrow R_{eq}(R_A, k_A, f) - Rf \\ \overrightarrow{D} \\ \overline{Rf} \end{array} \right\|$$

$$Error_L(R_A, k_A, f) := \left\| \begin{array}{l} Lf \leftarrow LF(f) \\ D \leftarrow L_{eq}(R_A, k_A, f) - Lf \\ \overrightarrow{D} \\ \overline{Lf} \end{array} \right\|$$

Vectors of zeros used in the Minerr block.

$$Z := \begin{bmatrix} Z \\ \frac{N^2 + N}{2} \leftarrow 0 \\ Z \end{bmatrix}$$

$$Zk := \begin{bmatrix} Z \\ \frac{N^2 - N}{2} \leftarrow 0 \\ Z \end{bmatrix}$$

Define a function for calculating the coupling matrix of the equivalent circuit.

$$K_{mod}(k_A) := \begin{bmatrix} K \leftarrow \text{identity}(N + N_{aux}) \\ \text{for } m \in 1 \dots N \\ \quad \text{for } n \in 1 \dots N \\ \quad \quad K_{m,n} \leftarrow Kb_{m,n} \\ a \leftarrow 1 \\ \text{for } row \in 1 \dots N \\ \quad \text{for } col \in N + 1 \dots N + N_{aux} \\ \quad \quad K_{row,col} \leftarrow k_{A_a} \\ \quad \quad K_{col,row} \leftarrow k_{A_a} \\ \quad \quad a \leftarrow a + 1 \\ K \end{bmatrix}$$

Define function for computing the eigenvalues of the model coupling matrix.

$$EigenTest(k_A) := \begin{bmatrix} EV \leftarrow \text{eigenvals}(K_{mod}(k_A)) \\ EV \end{bmatrix}$$

$$EigenTest(k_A) = \begin{bmatrix} 3.988 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 0.008 \\ 0.002 \\ 0.001 \end{bmatrix}$$

Define function for determining the if there is a negative eigenvalue for the model coupling matrix. This helps the solver find solutions that are physically realizable, which requires all of the eigenvalues to be positive [2]. The 1000000 multiplier gives it a high weight in the solver.

$$EigenSign(k_A) := \left\| \begin{array}{l} ET \leftarrow \min(EigenTest(k_A)) \\ \frac{10000000 \cdot ET}{|ET|} \end{array} \right\| \quad EigenSign(k_A) = 1 \cdot 10^7$$

Error Weighting

$c := 10$

$d := 100$

$e := 1$

Guess Values

$$d \cdot Error_R(R_A, k_A, 1) = Z$$

$$d \cdot Error_R(R_A, k_A, 5) = Z$$

$$d \cdot Error_R(R_A, k_A, 10) = Z$$

$$d \cdot Error_R(R_A, k_A, 2) = Z$$

$$d \cdot Error_R(R_A, k_A, 6) = Z$$

$$d \cdot Error_R(R_A, k_A, 12) = Z$$

$$d \cdot Error_R(R_A, k_A, 3) = Z$$

$$d \cdot Error_R(R_A, k_A, 7) = Z$$

$$d \cdot Error_R(R_A, k_A, 14) = Z$$

$$d \cdot Error_R(R_A, k_A, 4) = Z$$

$$d \cdot Error_R(R_A, k_A, 8) = Z$$

$$d \cdot Error_R(R_A, k_A, 16) = Z$$

$$c \cdot Error_L(R_A, k_A, 1) = Z$$

$$c \cdot Error_L(R_A, k_A, 5) = Z$$

$$c \cdot Error_L(R_A, k_A, 10) = Z$$

$$c \cdot Error_L(R_A, k_A, 2) = Z$$

$$c \cdot Error_L(R_A, k_A, 6) = Z$$

$$c \cdot Error_L(R_A, k_A, 12) = Z$$

$$c \cdot Error_L(R_A, k_A, 3) = Z$$

$$c \cdot Error_L(R_A, k_A, 7) = Z$$

$$c \cdot Error_L(R_A, k_A, 14) = Z$$

$$c \cdot Error_L(R_A, k_A, 4) = Z$$

$$c \cdot Error_L(R_A, k_A, 8) = Z$$

$$c \cdot Error_L(R_A, k_A, 16) = Z$$

$$e \cdot Error_K(R_A, k_A, 1) = Zk$$

$$e \cdot Error_K(R_A, k_A, 5) = Zk$$

$$e \cdot Error_K(R_A, k_A, 10) = Zk$$

$$e \cdot Error_K(R_A, k_A, 2) = Zk$$

$$e \cdot Error_K(R_A, k_A, 6) = Zk$$

$$e \cdot Error_K(R_A, k_A, 12) = Zk$$

$$e \cdot Error_K(R_A, k_A, 3) = Zk$$

$$e \cdot Error_K(R_A, k_A, 7) = Zk$$

$$e \cdot Error_K(R_A, k_A, 14) = Zk$$

$$e \cdot Error_K(R_A, k_A, 4) = Zk$$

$$e \cdot Error_K(R_A, k_A, 8) = Zk$$

$$e \cdot Error_K(R_A, k_A, 16) = Zk$$

traints

Constraints on coupling coefficients and resistors prevent inappropriate component values.

Cons

$$\begin{array}{cccccc}
-1 < k_{A_1} < 1 & -1 < k_{A_9} < 1 & -1 < k_{A_{17}} < 1 & -1 < k_{A_{25}} < 1 & -1 < k_{A_{33}} < 1 & -1 < k_{A_{41}} < 1 \\
-1 < k_{A_2} < 1 & -1 < k_{A_{10}} < 1 & -1 < k_{A_{18}} < 1 & -1 < k_{A_{26}} < 1 & -1 < k_{A_{34}} < 1 & -1 < k_{A_{42}} < 1 \\
-1 < k_{A_3} < 1 & -1 < k_{A_{11}} < 1 & -1 < k_{A_{19}} < 1 & -1 < k_{A_{27}} < 1 & -1 < k_{A_{35}} < 1 & -1 < k_{A_{43}} < 1 \\
-1 < k_{A_4} < 1 & -1 < k_{A_{12}} < 1 & -1 < k_{A_{20}} < 1 & -1 < k_{A_{28}} < 1 & -1 < k_{A_{36}} < 1 & -1 < k_{A_{44}} < 1 \\
-1 < k_{A_5} < 1 & -1 < k_{A_{13}} < 1 & -1 < k_{A_{21}} < 1 & -1 < k_{A_{29}} < 1 & -1 < k_{A_{37}} < 1 & -1 < k_{A_{45}} < 1 \\
-1 < k_{A_6} < 1 & -1 < k_{A_{14}} < 1 & -1 < k_{A_{22}} < 1 & -1 < k_{A_{30}} < 1 & -1 < k_{A_{38}} < 1 & -1 < k_{A_{46}} < 1 \\
-1 < k_{A_7} < 1 & -1 < k_{A_{15}} < 1 & -1 < k_{A_{23}} < 1 & -1 < k_{A_{31}} < 1 & -1 < k_{A_{39}} < 1 & -1 < k_{A_{47}} < 1 \\
-1 < k_{A_8} < 1 & -1 < k_{A_{16}} < 1 & -1 < k_{A_{24}} < 1 & -1 < k_{A_{32}} < 1 & -1 < k_{A_{40}} < 1 & -1 < k_{A_{48}} < 1
\end{array}$$

$$10^4 \cdot R_{A_1} > 10^4 \cdot \Omega \quad 10^4 \cdot R_{A_4} > 10^4 \cdot \Omega \quad 10^4 \cdot R_{A_7} > 10^4 \cdot \Omega \quad 10^4 \cdot R_{A_{10}} > 10^4 \cdot \Omega$$

$$10^4 \cdot R_{A_2} > 10^4 \cdot \Omega \quad 10^4 \cdot R_{A_5} > 10^4 \cdot \Omega \quad 10^4 \cdot R_{A_8} > 10^4 \cdot \Omega \quad 10^4 \cdot R_{A_{11}} > 10^4 \cdot \Omega$$

$$10^4 \cdot R_{A_3} > 10^4 \cdot \Omega \quad 10^4 \cdot R_{A_6} > 10^4 \cdot \Omega \quad 10^4 \cdot R_{A_9} > 10^4 \cdot \Omega \quad 10^4 \cdot R_{A_{12}} > 10^4 \cdot \Omega$$

$$EigenSign(k_A) > 10000000$$

Solver

$$\begin{bmatrix} R_A \\ k_A \end{bmatrix} := \mathbf{Minerr}(R_A, k_A)$$

ERR = ?

$$R_A = \begin{bmatrix} 6.2985 \cdot 10^3 \\ 7.8203 \\ 1.0999 \cdot 10^3 \\ 2.5839 \\ 19.9783 \\ 714.0522 \\ 4.7455 \\ 93.2466 \\ 1.1474 \cdot 10^3 \\ 990.8804 \\ 689.1785 \\ 6.8748 \cdot 10^3 \end{bmatrix} \Omega$$

$$Kb = \begin{bmatrix} 1.00000 & 0.99797 & 0.99567 & 0.99271 \\ 0.99797 & 1.00000 & 0.99801 & 0.99494 \\ 0.99567 & 0.99801 & 1.00000 & 0.99729 \\ 0.99271 & 0.99494 & 0.99729 & 1.00000 \end{bmatrix}$$

$$\text{eigenvals} \langle K_{mod} \langle k_A \rangle \rangle = \begin{bmatrix} 3.997343 \\ 1.002754 \\ 1.000616 \\ 1.000259 \\ 1.000000 \\ 1.000000 \\ 1.000000 \\ 1.000000 \\ 1.000000 \\ 1.000000 \\ 1.000000 \\ 0.991007 \\ 0.005448 \\ 0.001739 \\ 0.000835 \end{bmatrix}$$

If negative eigenvalues values are present then the realizability criterion is violated [2].

Computed auxiliary couplings

$$k_{A1} := \left\| \begin{array}{l} \text{for } h \in 1 \dots 24 \\ \left\| K_h \leftarrow k_{A_h} \right\| \\ K \end{array} \right\|$$

$$k_{A2} := \left\| \begin{array}{l} \text{for } h \in 25 \dots 48 \\ \left\| K_{h-24} \leftarrow k_{A_h} \right\| \\ K \end{array} \right\|$$

$$k_{A1} = \begin{bmatrix} 0.017475 \\ 0.060040 \\ 0.025927 \\ 0.010250 \\ 0.026161 \\ 0.007372 \\ 0.037492 \\ -0.005118 \\ -0.011724 \\ 0.006743 \\ 0.015337 \\ -0.021126 \\ -0.004076 \\ 0.061227 \\ 0.017061 \\ 0.004288 \\ 0.027130 \\ 0.017020 \\ 0.037731 \\ 0.006594 \\ -0.007198 \\ 0.020079 \\ 0.008054 \\ -0.027815 \end{bmatrix}$$

$$k_{A2} = \begin{bmatrix} -0.000909 \\ 0.061048 \\ -0.012117 \\ -0.004399 \\ 0.027236 \\ 0.018211 \\ 0.037741 \\ -0.003857 \\ 0.005974 \\ 0.022661 \\ 0.007792 \\ -0.027567 \\ -0.012471 \\ 0.059212 \\ -0.023859 \\ -0.012629 \\ 0.026099 \\ -0.007614 \\ 0.037434 \\ 0.005979 \\ 0.011059 \\ 0.007158 \\ 0.015912 \\ -0.020175 \end{bmatrix}$$

Extract resistance and inductance values of the equivalent circuit for plotting.

$$R11eq_f := R_{eq}(R_A, k_A, f)_1$$

$$L11eq_f := L_{eq}(R_A, k_A, f)_1$$

$$R22eq_f := R_{eq}(R_A, k_A, f)_2$$

$$L22eq_f := L_{eq}(R_A, k_A, f)_2$$

$$R33eq_f := R_{eq}(R_A, k_A, f)_3$$

$$L33eq_f := L_{eq}(R_A, k_A, f)_3$$

$$R44eq_f := R_{eq}(R_A, k_A, f)_4$$

$$L44eq_f := L_{eq}(R_A, k_A, f)_4$$

$$R12eq_f := R_{eq}(R_A, k_A, f)_5$$

$$L12eq_f := L_{eq}(R_A, k_A, f)_5$$

$$R13eq_f := R_{eq}(R_A, k_A, f)_6$$

$$L13eq_f := L_{eq}(R_A, k_A, f)_6$$

$$R14eq_f := R_{eq}(R_A, k_A, f)_7$$

$$L14eq_f := L_{eq}(R_A, k_A, f)_7$$

$$R23eq_f := R_{eq}(R_A, k_A, f)_8$$

$$L23eq_f := L_{eq}(R_A, k_A, f)_8$$

$$R24eq_f := R_{eq}(R_A, k_A, f)_9$$

$$L24eq_f := L_{eq}(R_A, k_A, f)_9$$

$$R34eq_f := R_{eq}(R_A, k_A, f)_{10}$$

$$L34eq_f := L_{eq}(R_A, k_A, f)_{10}$$

Equivalent Circuit mutual resistance couplings

$$kr12eq_f := kreq(R_A, k_A, f)_1$$

$$kr13eq_f := kreq(R_A, k_A, f)_2$$

$$kr14eq_f := kreq(R_A, k_A, f)_3$$

$$kr23eq_f := kreq(R_A, k_A, f)_4$$

$$kr24eq_f := kreq(R_A, k_A, f)_5$$

$$kr34eq_f := kreq(R_A, k_A, f)_6$$

Equivalent circuit leakage resistances and inductances

$$R_{leak12eq_f} := R_{leak12EQ}(R_A, k_A, f)$$

$$L_{leak12eq_f} := L_{leak12EQ}(R_A, k_A, f)$$

$$R_{leak13eq_f} := R_{leak13EQ}(R_A, k_A, f)$$

$$L_{leak13eq_f} := L_{leak13EQ}(R_A, k_A, f)$$

$$R_{leak14eq_f} := R_{leak14EQ}(R_A, k_A, f)$$

$$L_{leak14eq_f} := L_{leak14EQ}(R_A, k_A, f)$$

$$R_{leak23eq_f} := R_{leak23EQ}(R_A, k_A, f)$$

$$L_{leak23eq_f} := L_{leak23EQ}(R_A, k_A, f)$$

$$R_{leak24eq_f} := R_{leak24EQ}(R_A, k_A, f)$$

$$L_{leak24eq_f} := L_{leak24EQ}(R_A, k_A, f)$$

$$R_{leak34eq_f} := R_{leak34EQ}(R_A, k_A, f)$$

$$L_{leak34eq_f} := L_{leak34EQ}(R_A, k_A, f)$$

$$Q_{leak12_f} := \frac{\omega_f \cdot L_{leak12_f}}{R_{leak12_f}}$$

$$Q_{leak13_f} := \frac{\omega_f \cdot L_{leak13_f}}{R_{leak13_f}}$$

$$Q_{leak14_f} := \frac{\omega_f \cdot L_{leak14_f}}{R_{leak14_f}}$$

$$Q_{leak23_f} := \frac{\omega_f \cdot L_{leak23_f}}{R_{leak23_f}}$$

$$Q_{leak24_f} := \frac{\omega_f \cdot L_{leak24_f}}{R_{leak24eq_f}}$$

$$Q_{leak34_f} := \frac{\omega_f \cdot L_{leak34_f}}{R_{leak34_f}}$$

Create an equivalent circuit resistive coupling matrix and see if there are any negative eigenvalues.

$$KReq(f) := \begin{bmatrix} 1 & kr12eq_f & kr13eq_f & kr14eq_f \\ kr12eq_f & 1 & kr23eq_f & kr24eq_f \\ kr13eq_f & kr23eq_f & 1 & kr23eq_f \\ kr14eq_f & kr24eq_f & kr34eq_f & 1 \end{bmatrix}$$

$$\text{eigenvals}(KReq(1)) = \begin{bmatrix} 2.942 \\ 0.384 \\ 0.37 \\ 0.304 \end{bmatrix}$$

$$\text{eigenvals}(KReq(2)) = \begin{bmatrix} 3.143 \\ 0.326 \\ 0.292 \\ 0.238 \end{bmatrix}$$

$$\text{eigenvals}(KReq(3)) = \begin{bmatrix} 3.302 \\ 0.284 \\ 0.228 \\ 0.186 \end{bmatrix}$$

$$\text{eigenvals}(KReq(4)) = \begin{bmatrix} 3.423 \\ 0.253 \\ 0.178 \\ 0.145 \end{bmatrix}$$

$$\text{eigenvals}(KReq(5)) = \begin{bmatrix} 3.488 \\ 0.248 \\ 0.146 \\ 0.118 \end{bmatrix}$$

$$\text{eigenvals}(KReq(6)) = \begin{bmatrix} 3.486 \\ 0.282 \\ 0.13 \\ 0.102 \end{bmatrix}$$

$$\text{eigenvals}(KReq(7)) = \begin{bmatrix} 3.396 \\ 0.376 \\ 0.134 \\ 0.094 \end{bmatrix}$$

$$\text{eigenvals}(KReq(8)) = \begin{bmatrix} 3.186 \\ 0.554 \\ 0.162 \\ 0.098 \end{bmatrix}$$

$$\text{eigenvals}(KReq(9)) = \begin{bmatrix} 2.877 \\ 0.808 \\ 0.205 \\ 0.11 \end{bmatrix}$$

$$\text{eigenvals}(KReq(10)) = \begin{bmatrix} 2.578 \\ 1.064 \\ 0.237 \\ 0.121 \end{bmatrix}$$

$$\text{eigenvals}(KReq(11)) = \begin{bmatrix} 2.401 \\ 1.234 \\ 0.24 \\ 0.126 \end{bmatrix}$$

$$\text{eigenvals}(KReq(12)) = \begin{bmatrix} 2.38 \\ 1.278 \\ 0.22 \\ 0.122 \end{bmatrix}$$

$$\text{eigenvals}(KReq(13)) = \begin{bmatrix} 2.466 \\ 1.228 \\ 0.199 \\ 0.108 \end{bmatrix}$$

$$\text{eigenvals}(KReq(14)) = \begin{bmatrix} 2.568 \\ 1.157 \\ 0.186 \\ 0.088 \end{bmatrix}$$

$$\text{eigenvals}(KReq(15)) = \begin{bmatrix} 2.627 \\ 1.119 \\ 0.177 \\ 0.076 \end{bmatrix}$$

$$\text{eigenvals}(KReq(16)) = \begin{bmatrix} 2.64 \\ 1.117 \\ 0.171 \\ 0.072 \end{bmatrix}$$

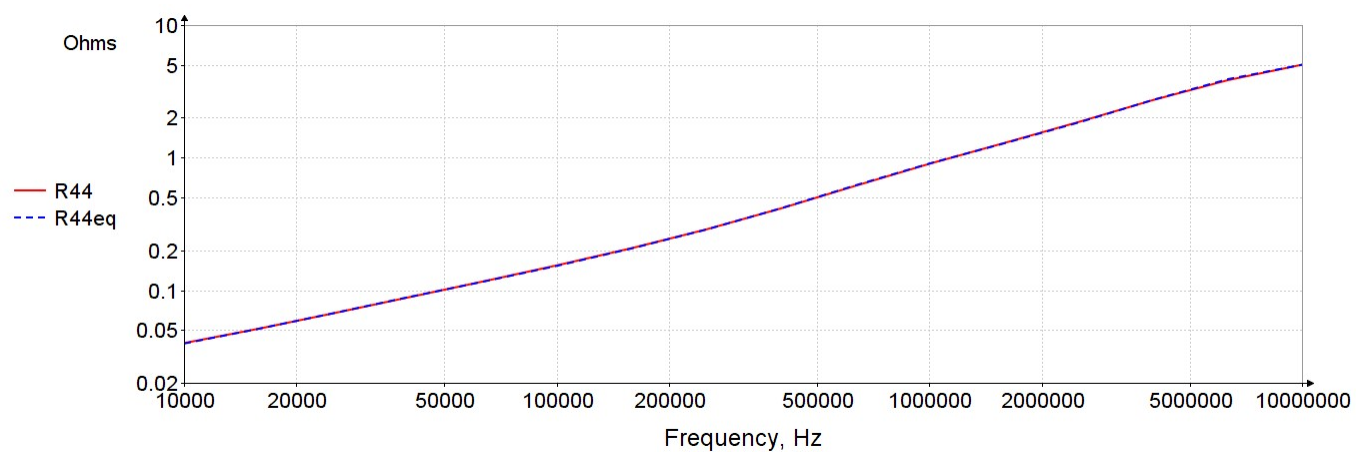
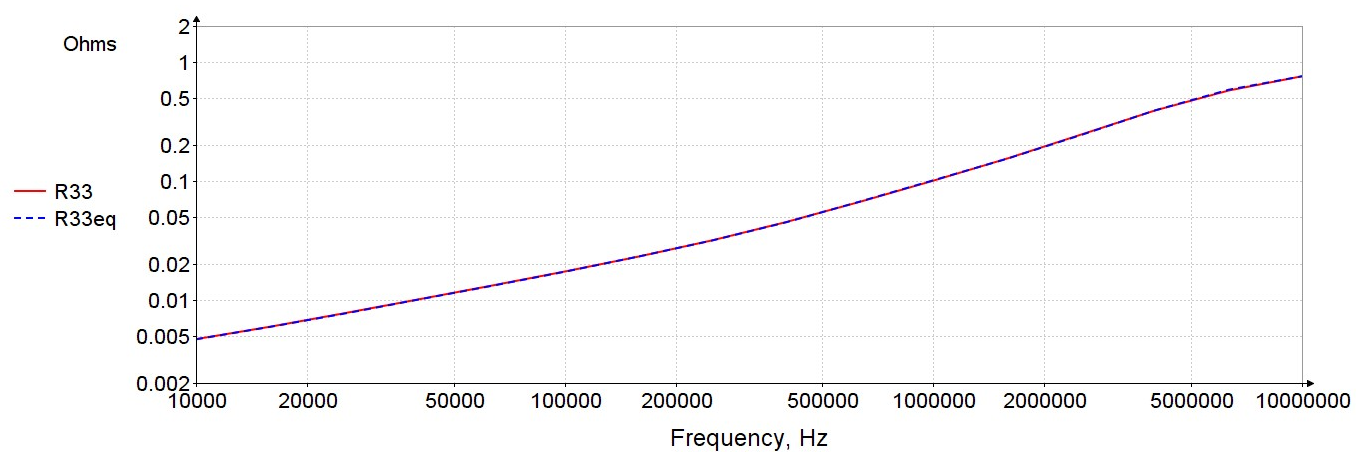
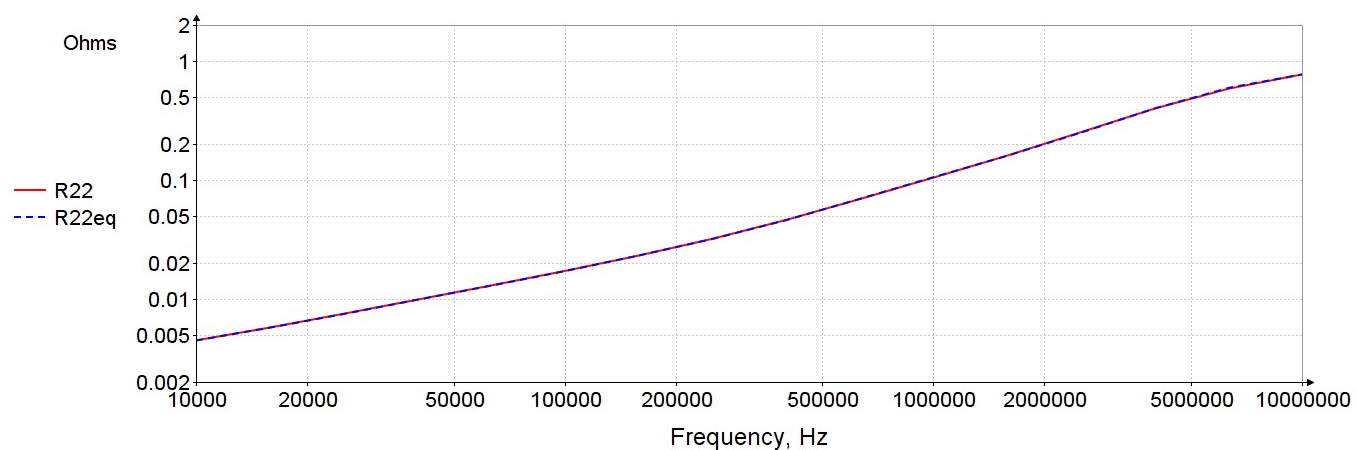
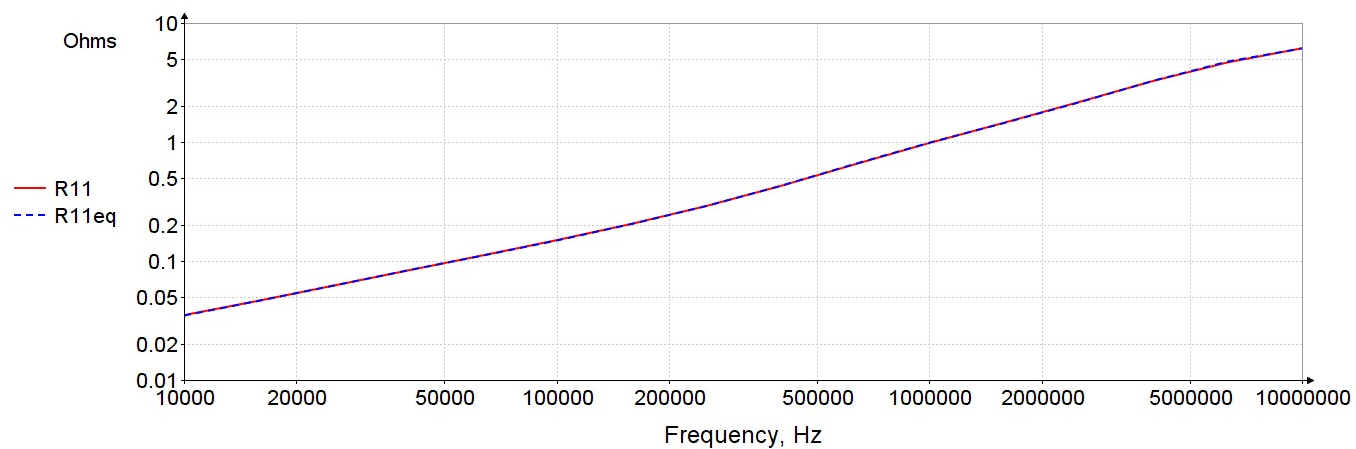


Figure 13. FEA and Equivalent Circuit self resistances.

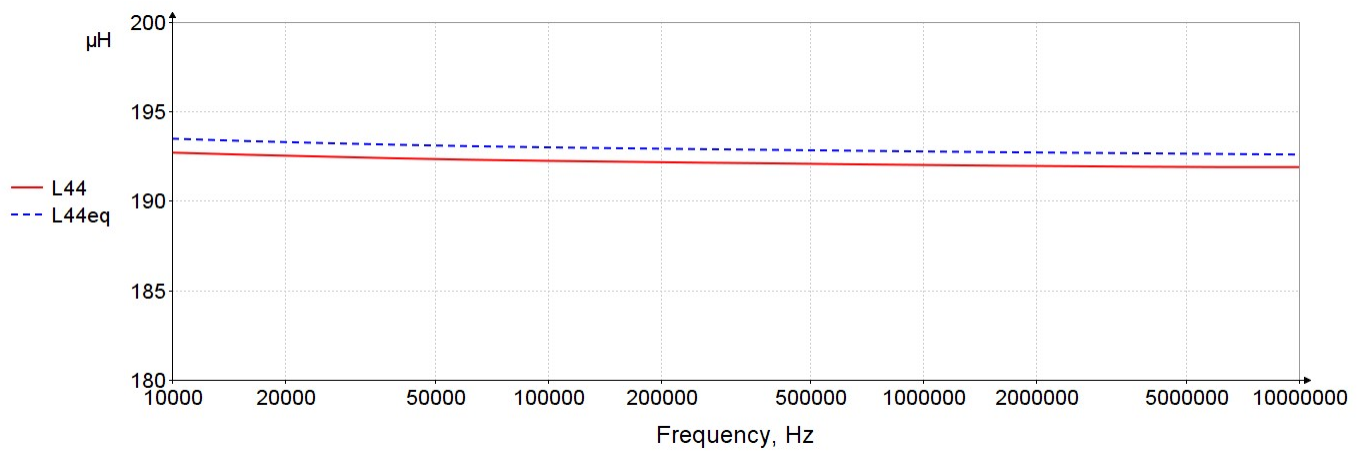
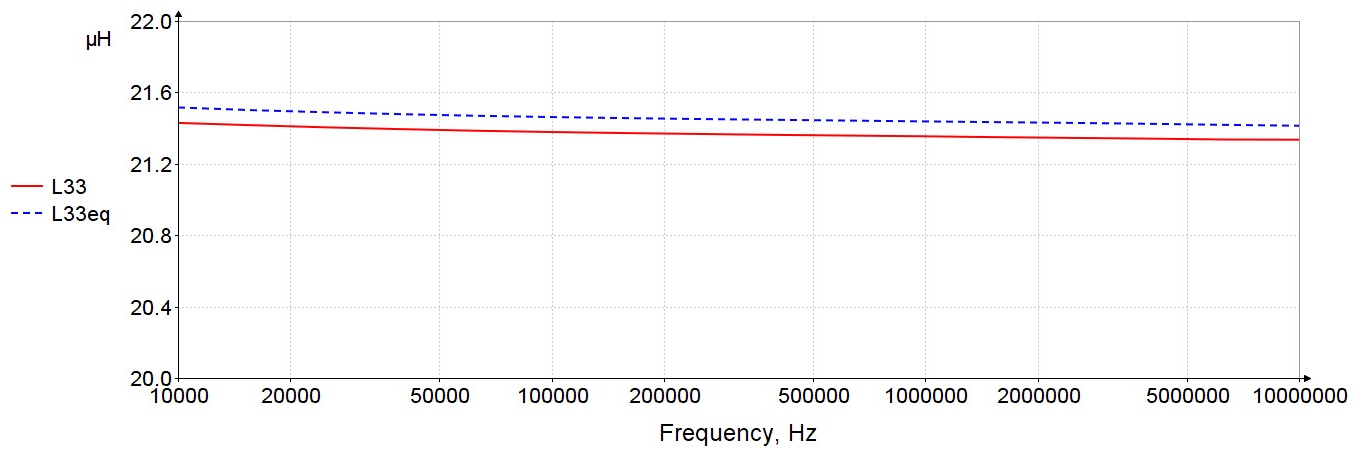
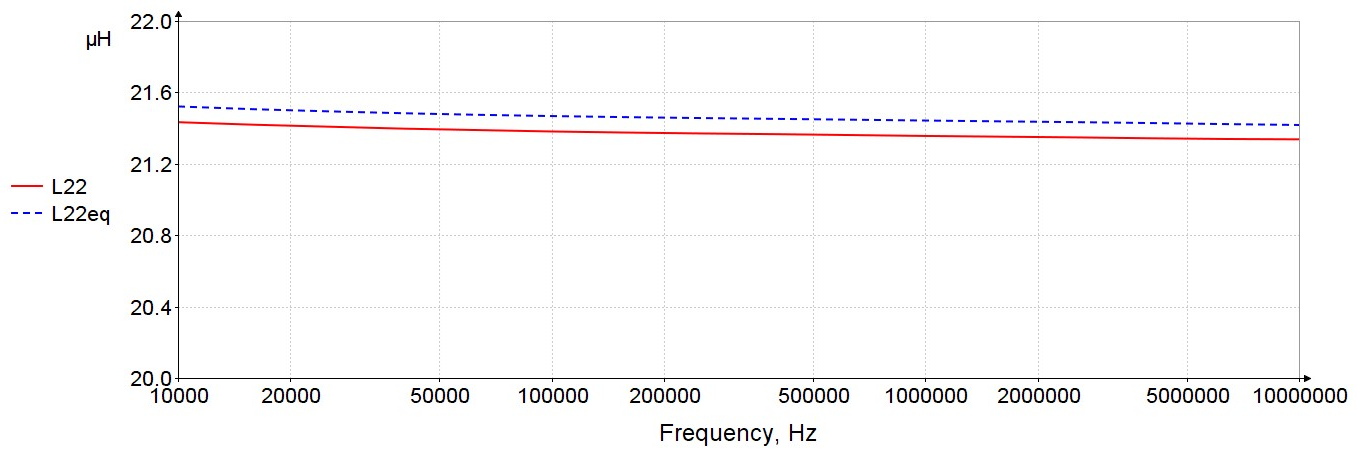
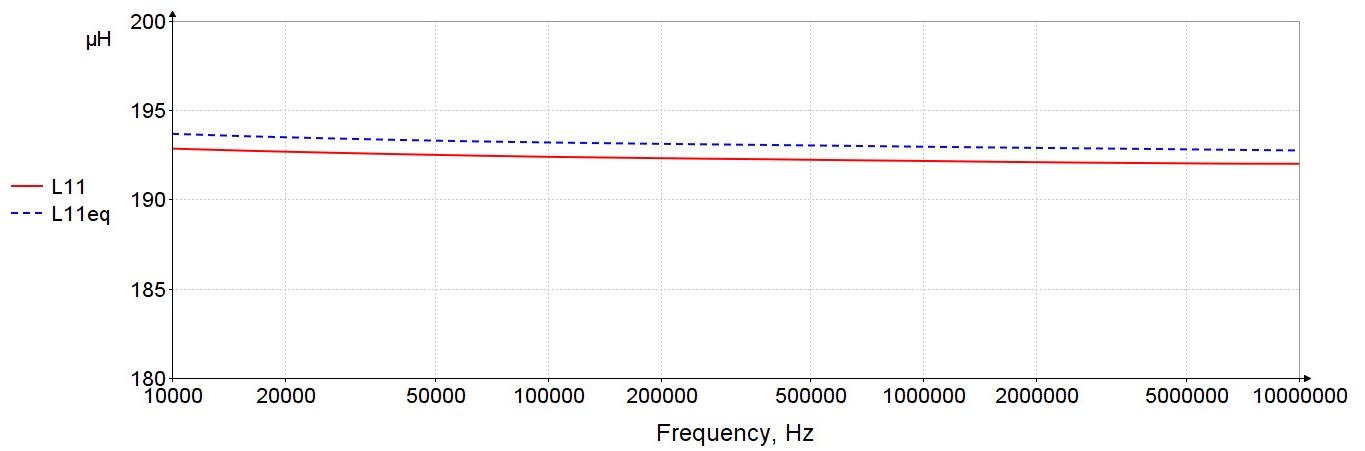


Figure 14. FEA and Equivalent Circuit self inductances.

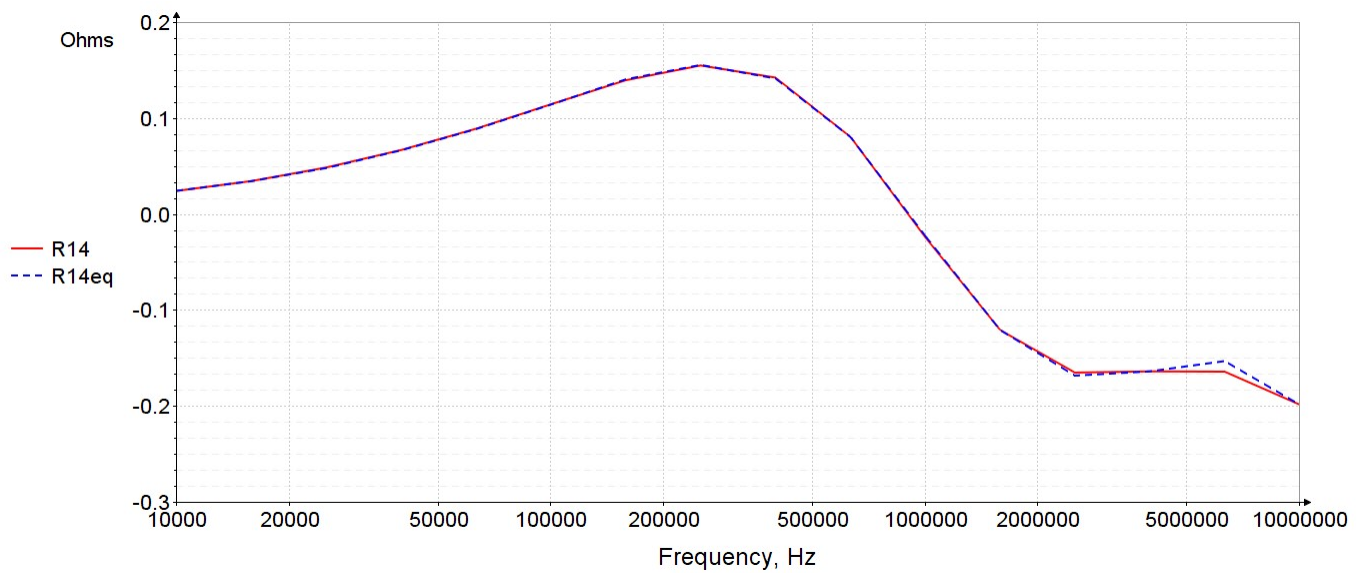
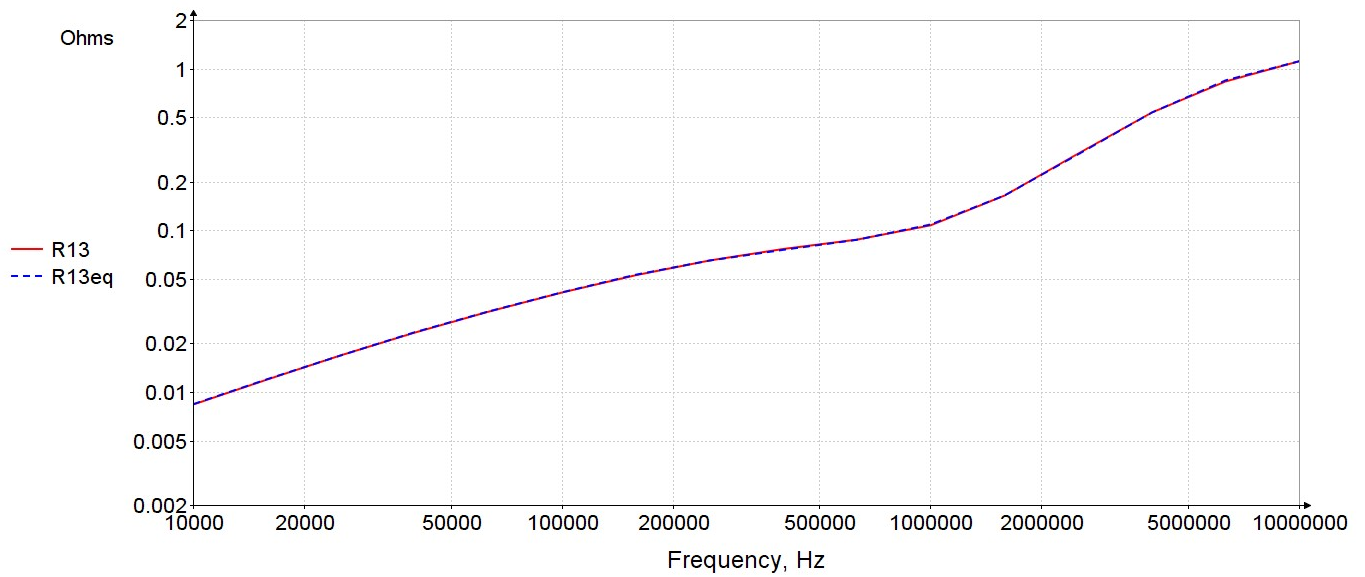
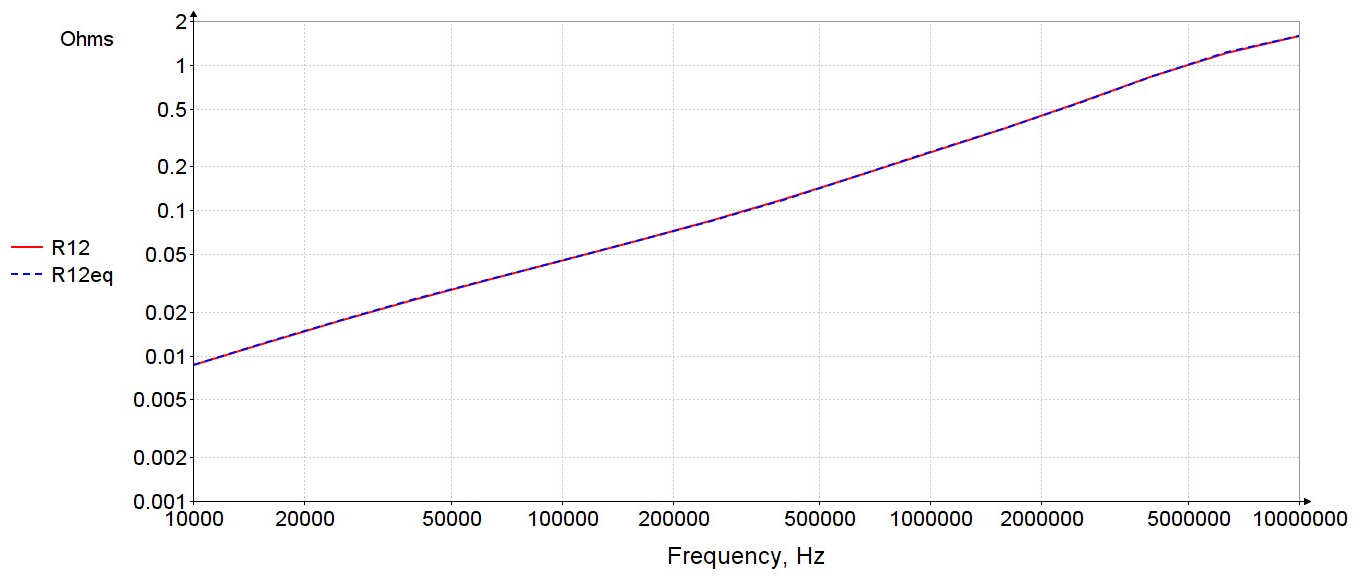


Figure 15a. FEA and Equivalent Circuit mutual resistances.

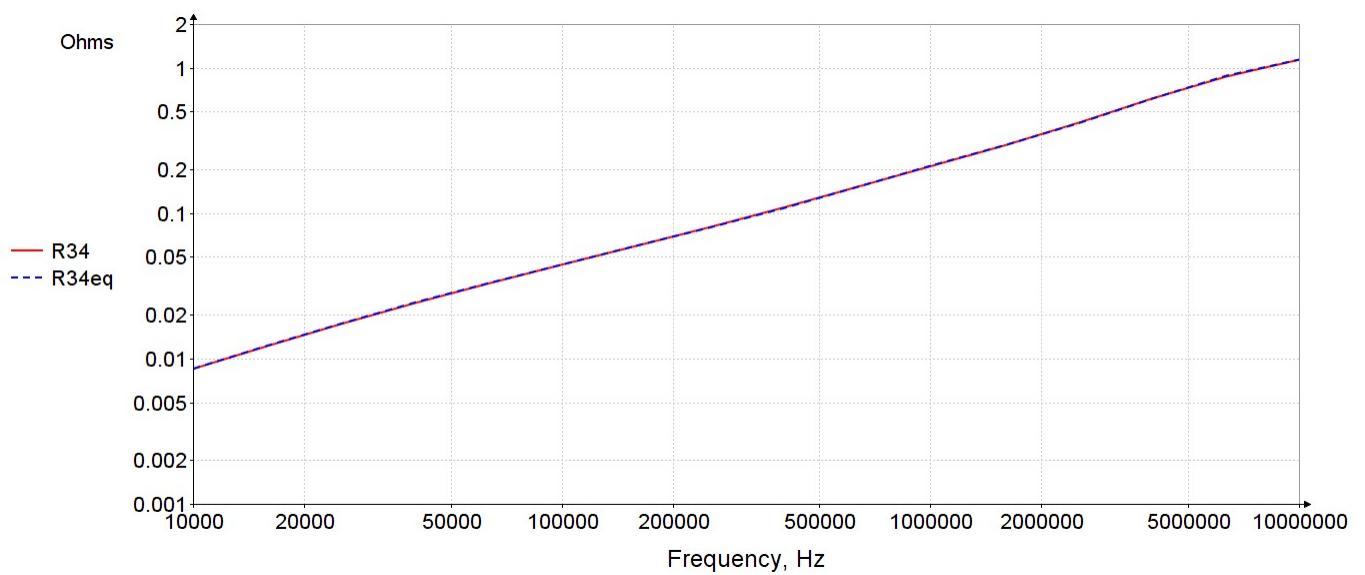
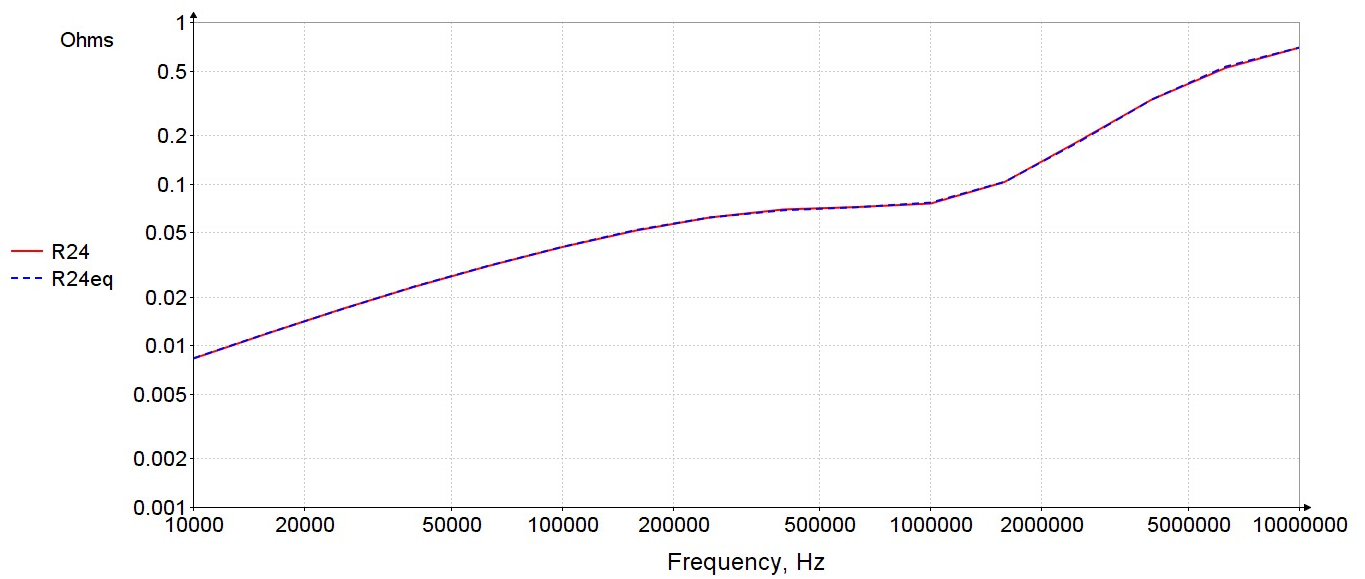
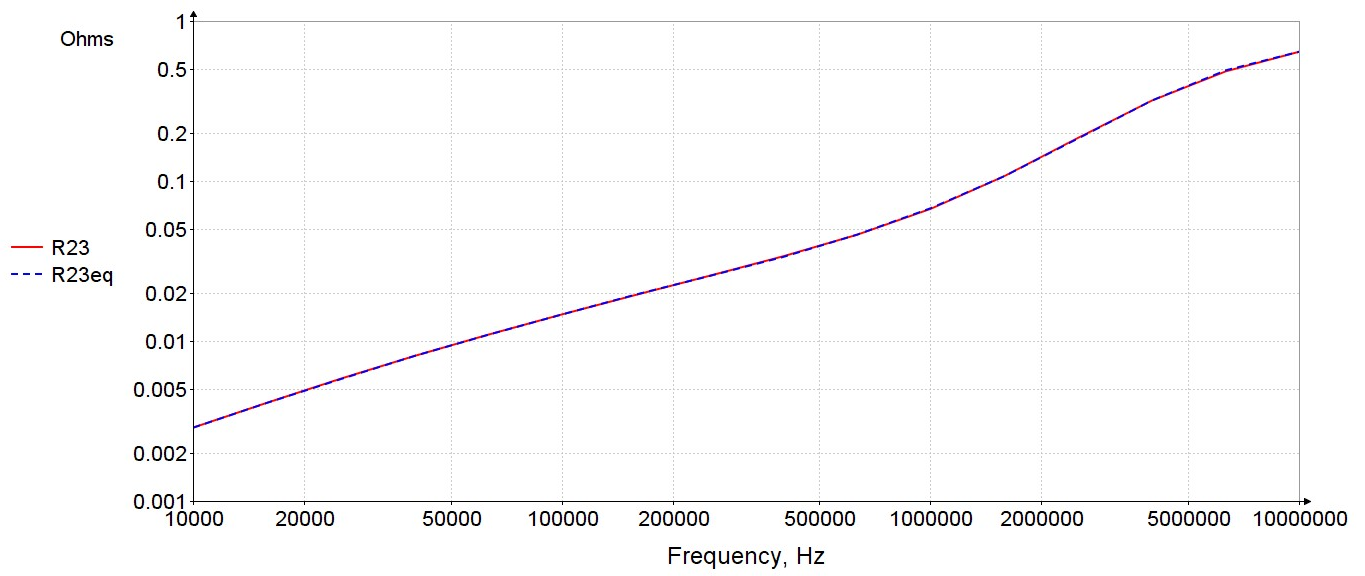


Figure 15b. FEA and Equivalent Circuit mutual resistances.

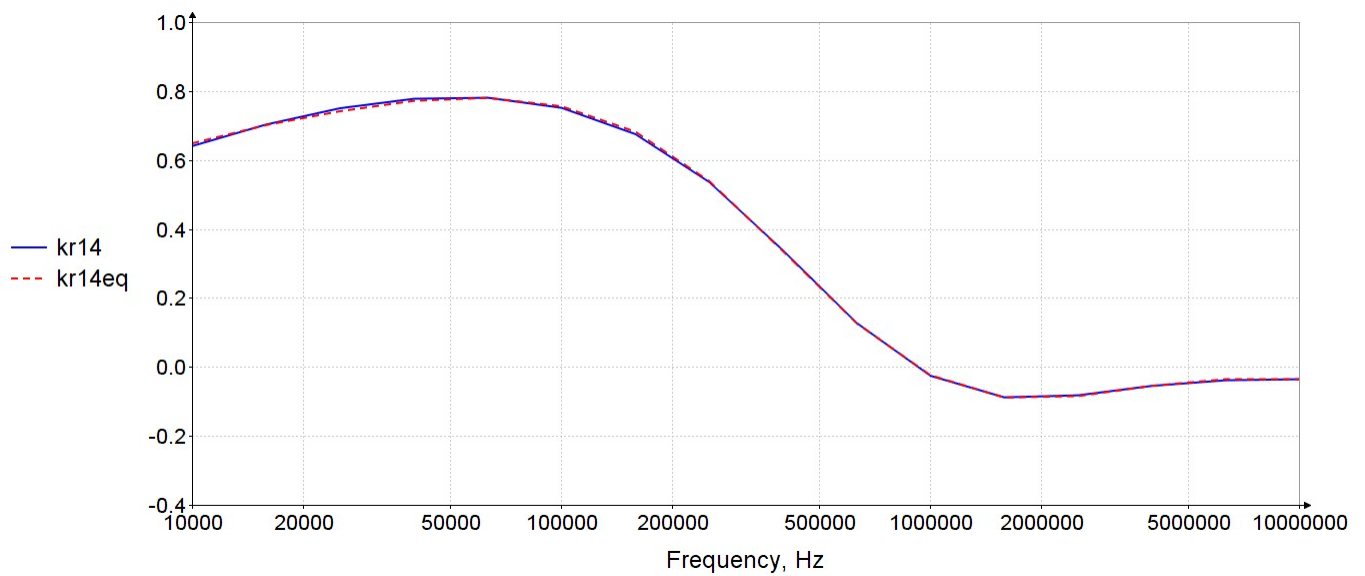
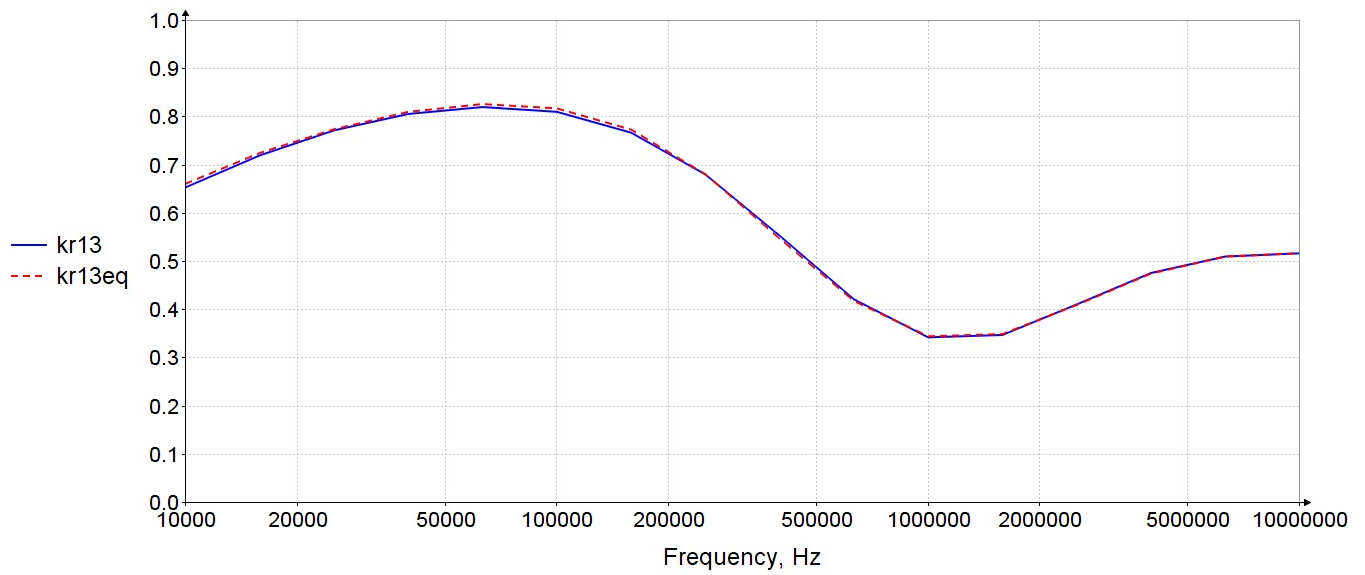
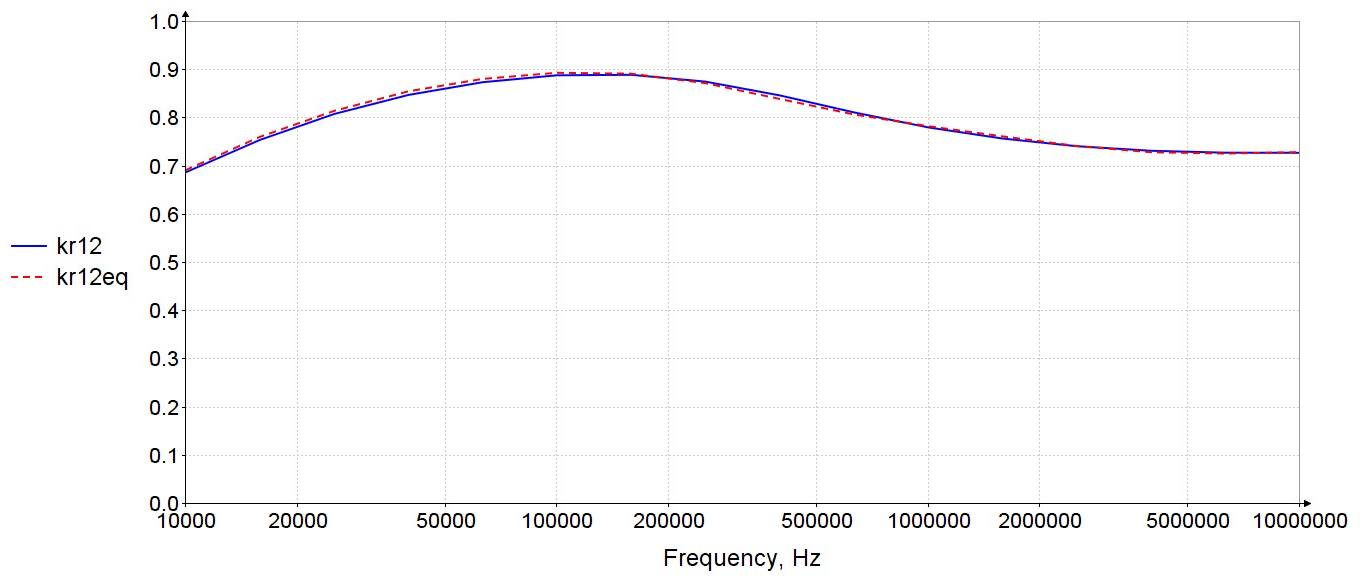


Figure 16a. FEA and Equivalent Circuit mutual resistance couplings.

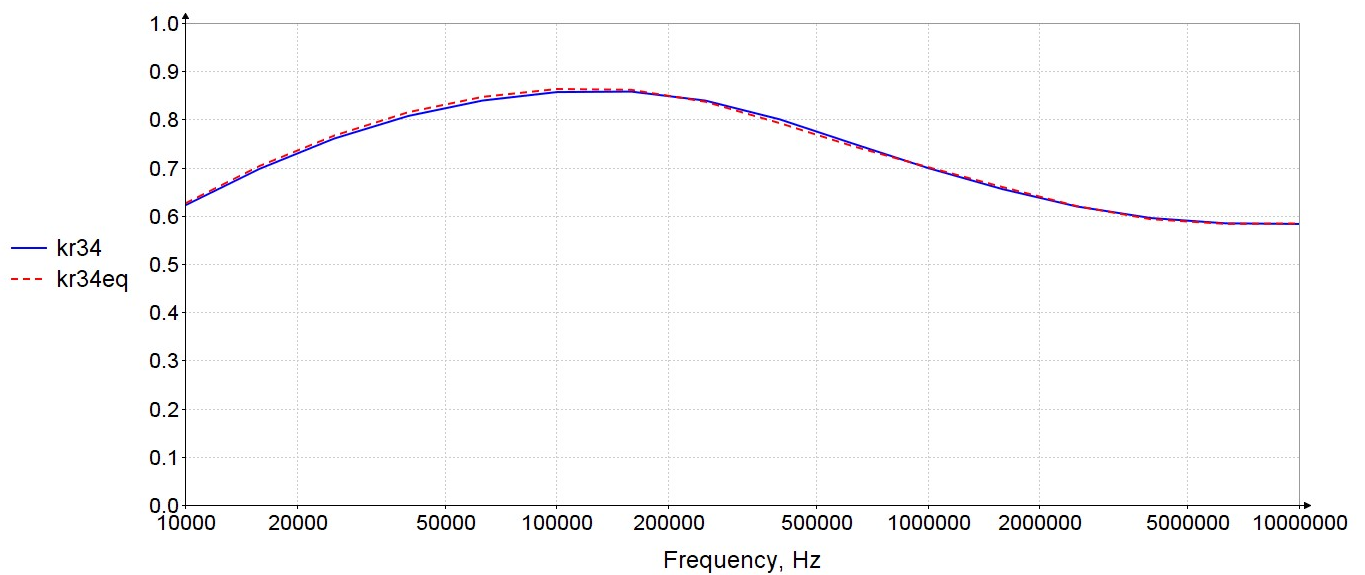
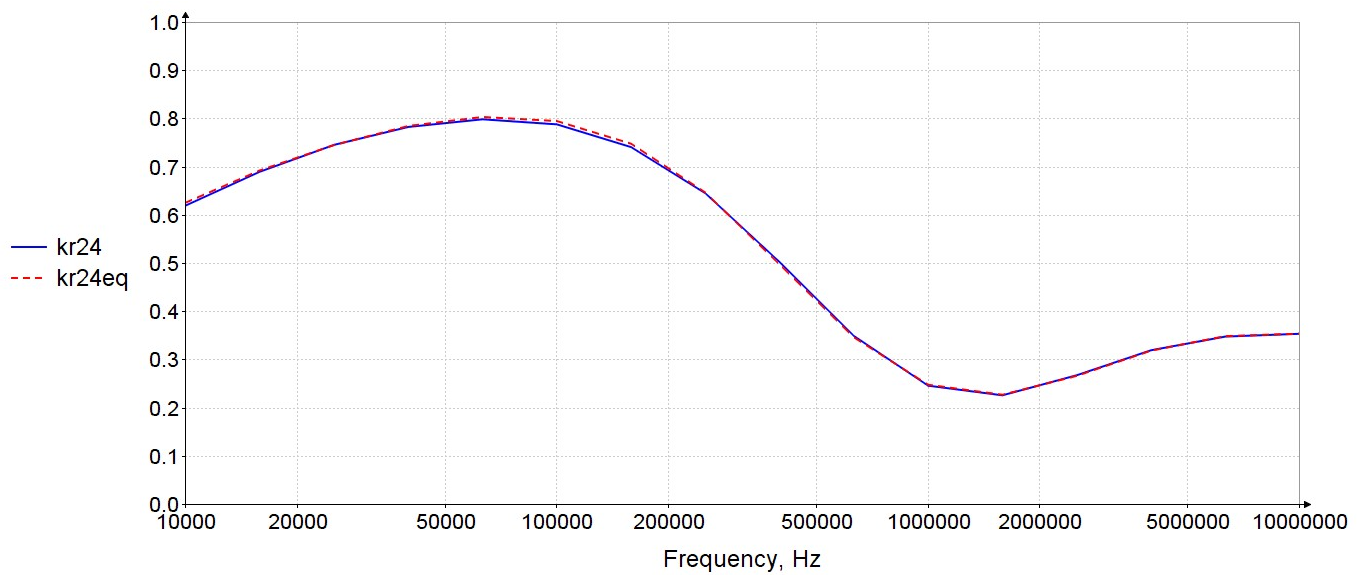
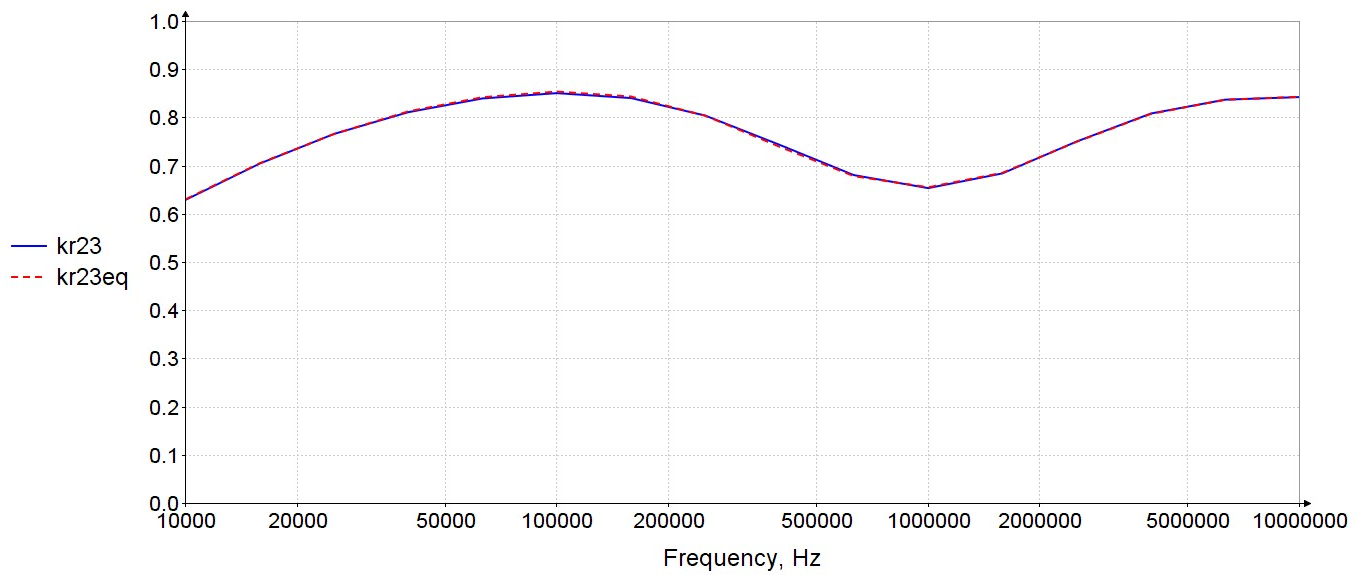


Figure 16b. FEA and Equivalent Circuit mutual resistance couplings.

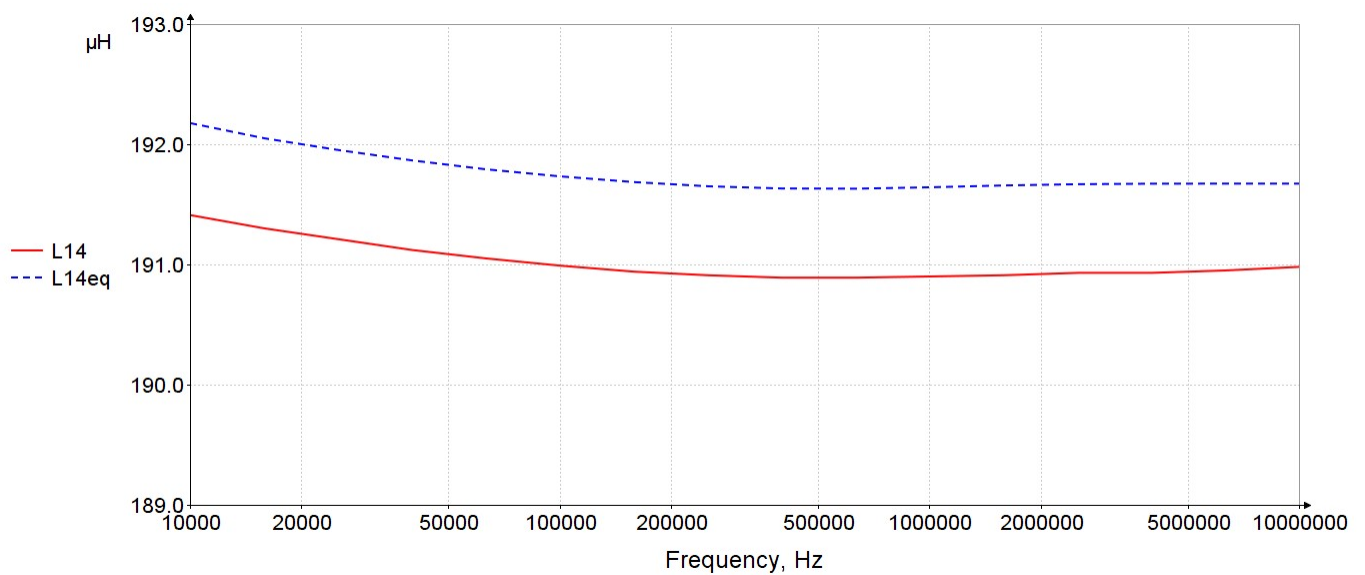
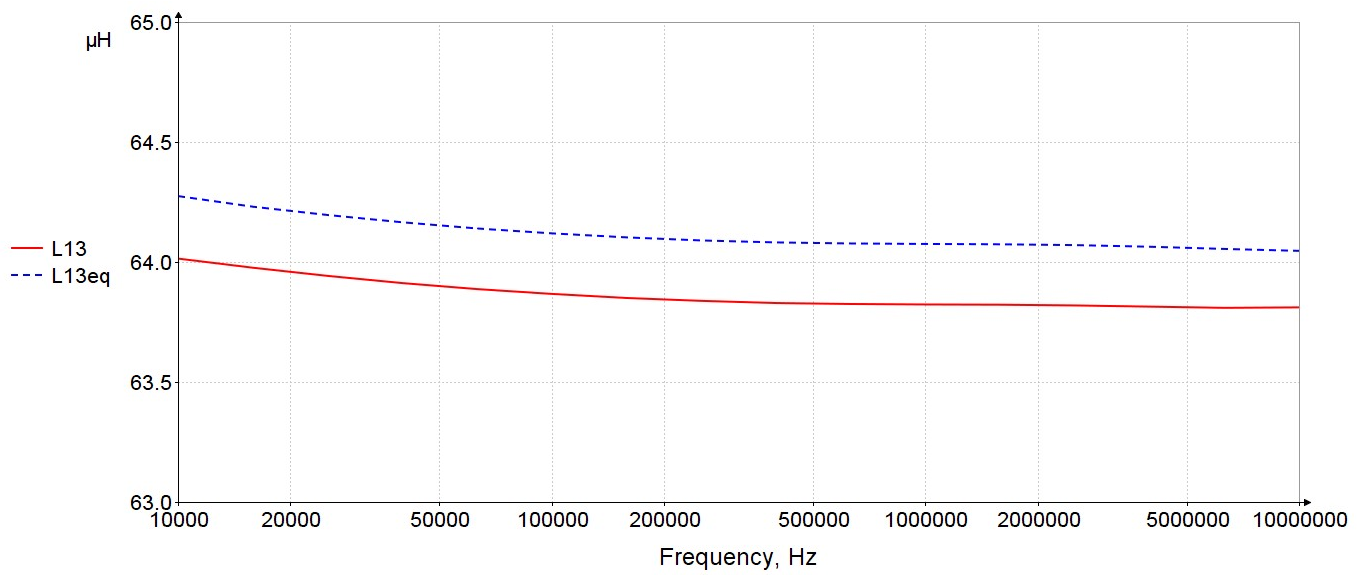
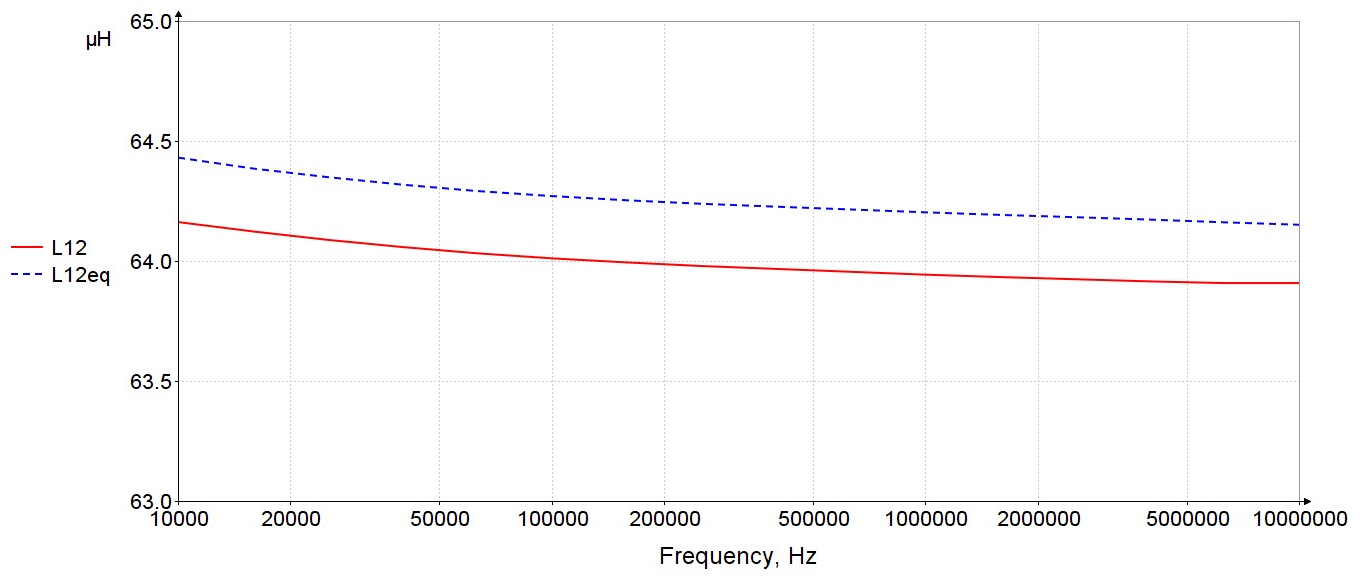


Figure 17a. FEA and Equivalent Circuit mutual inductances.

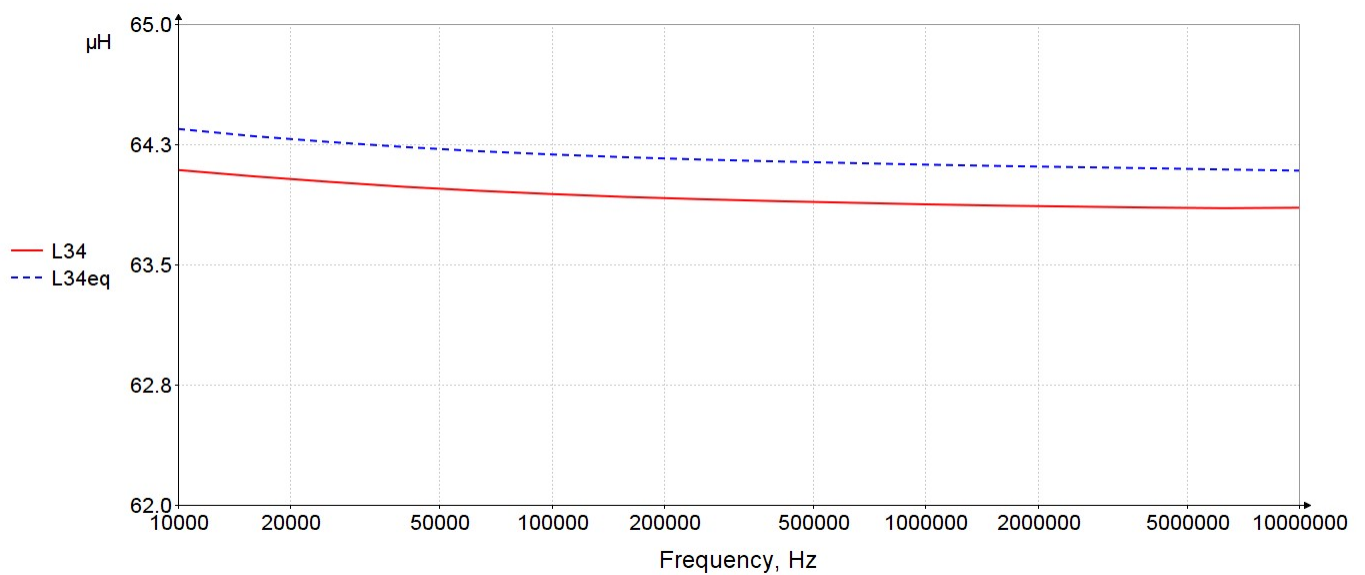
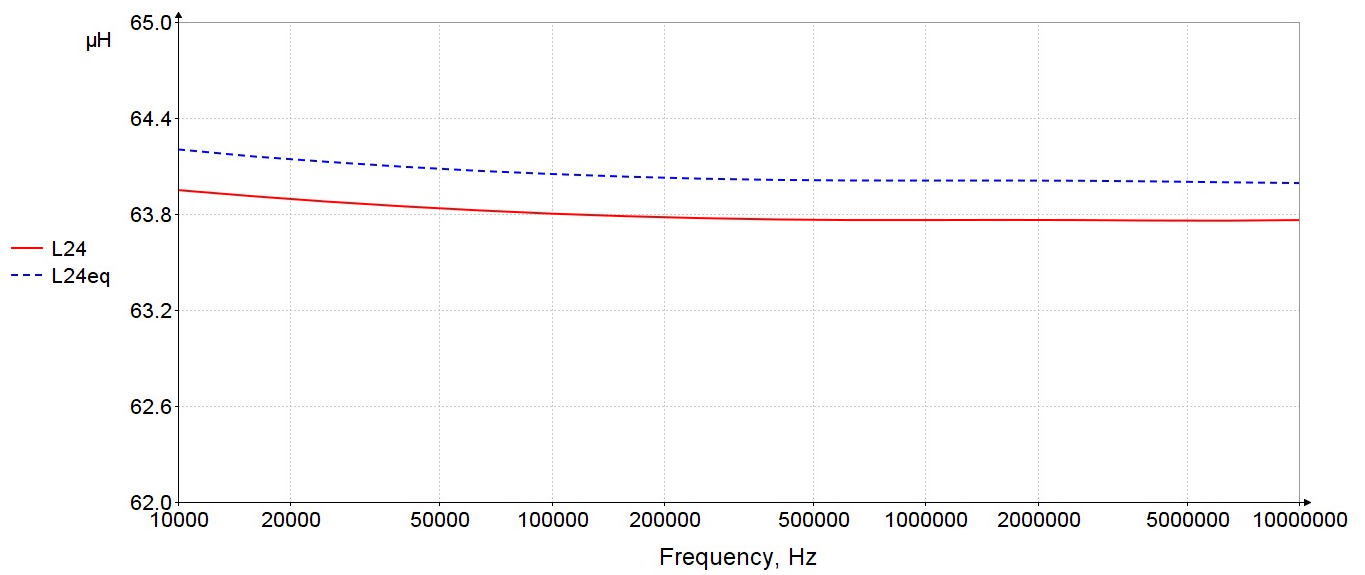
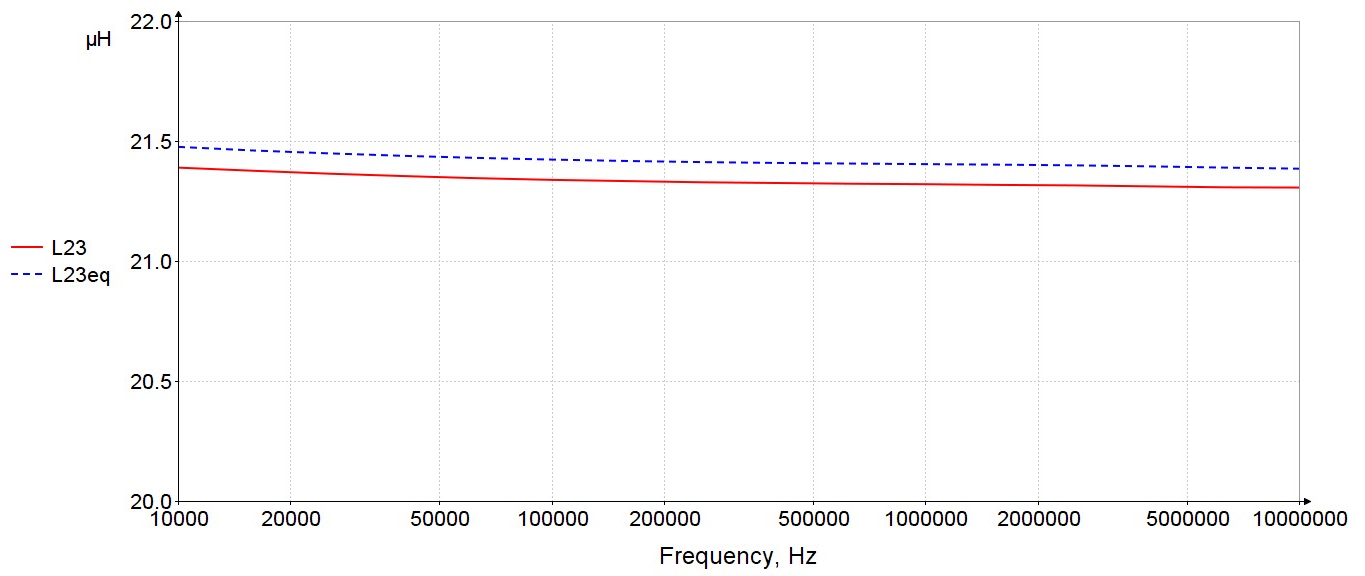


Figure 17b. FEA and Equivalent Circuit mutual inductances.

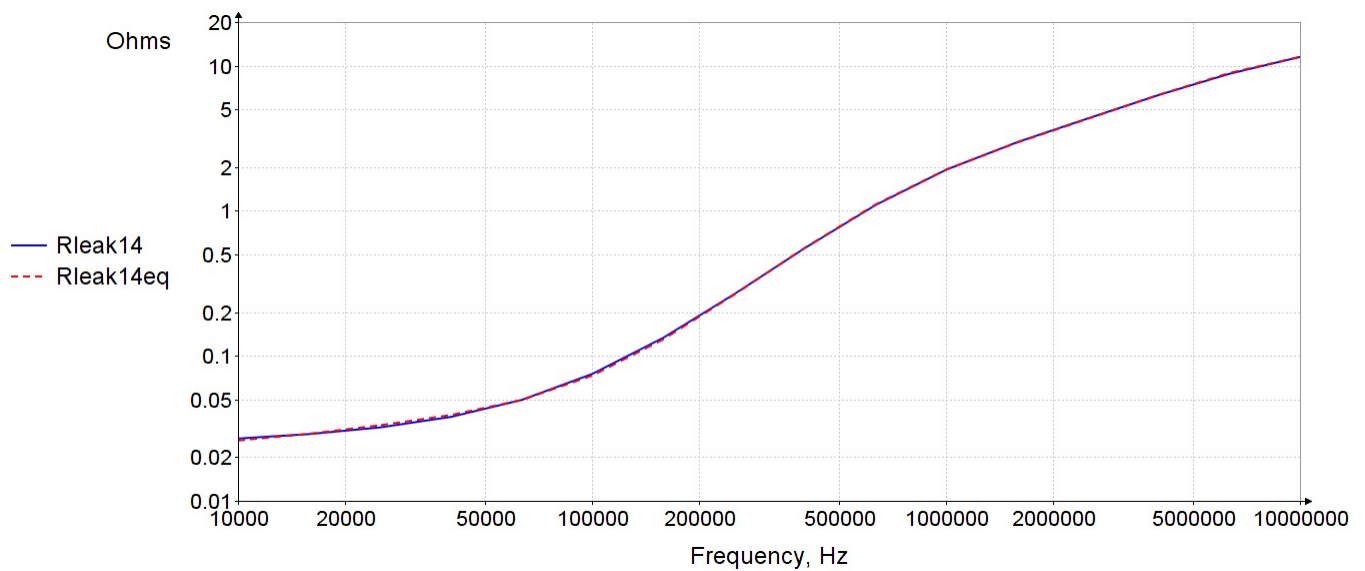
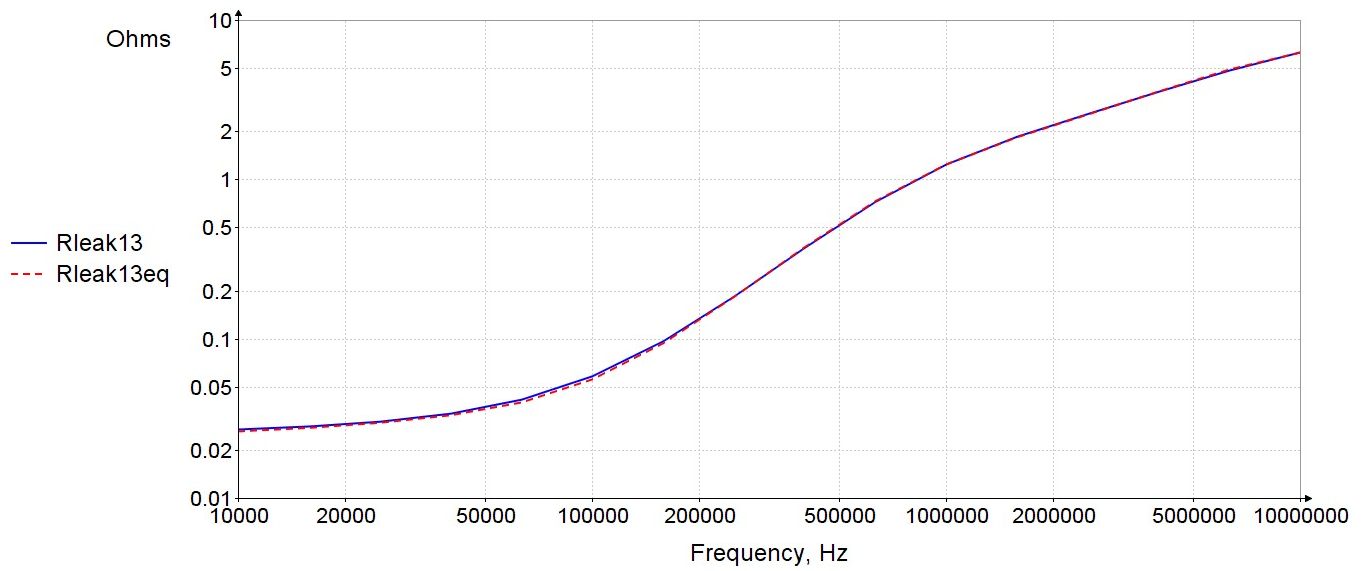
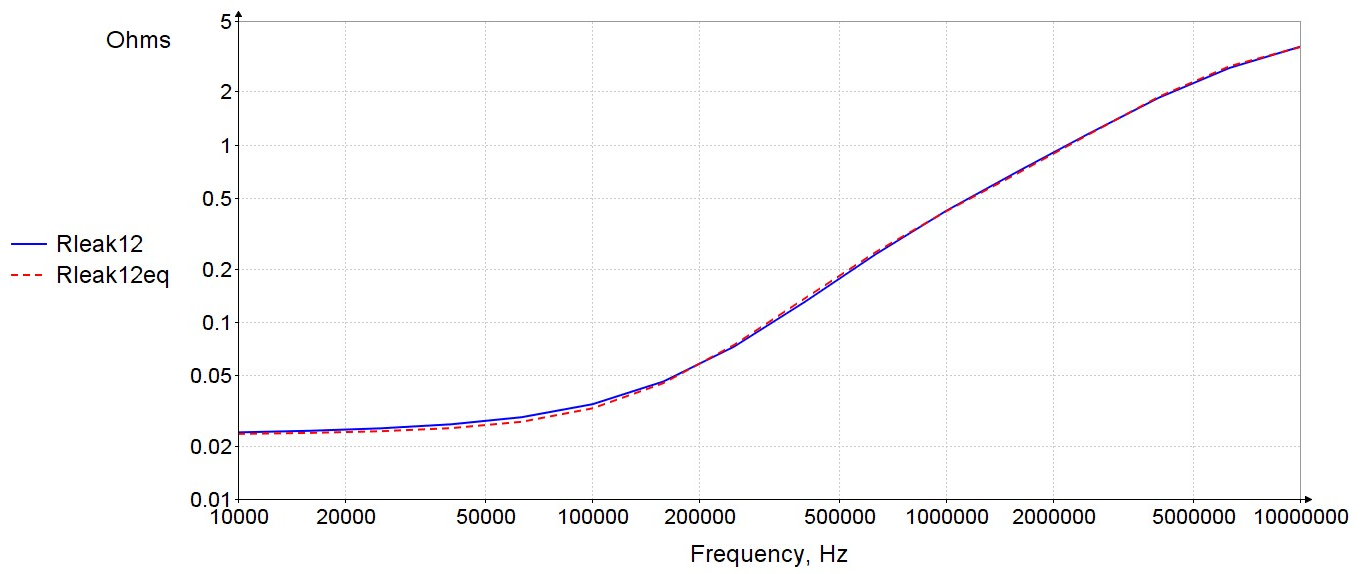


Fig. 18a. FEA and Equivalent Circuit leakage resistances.

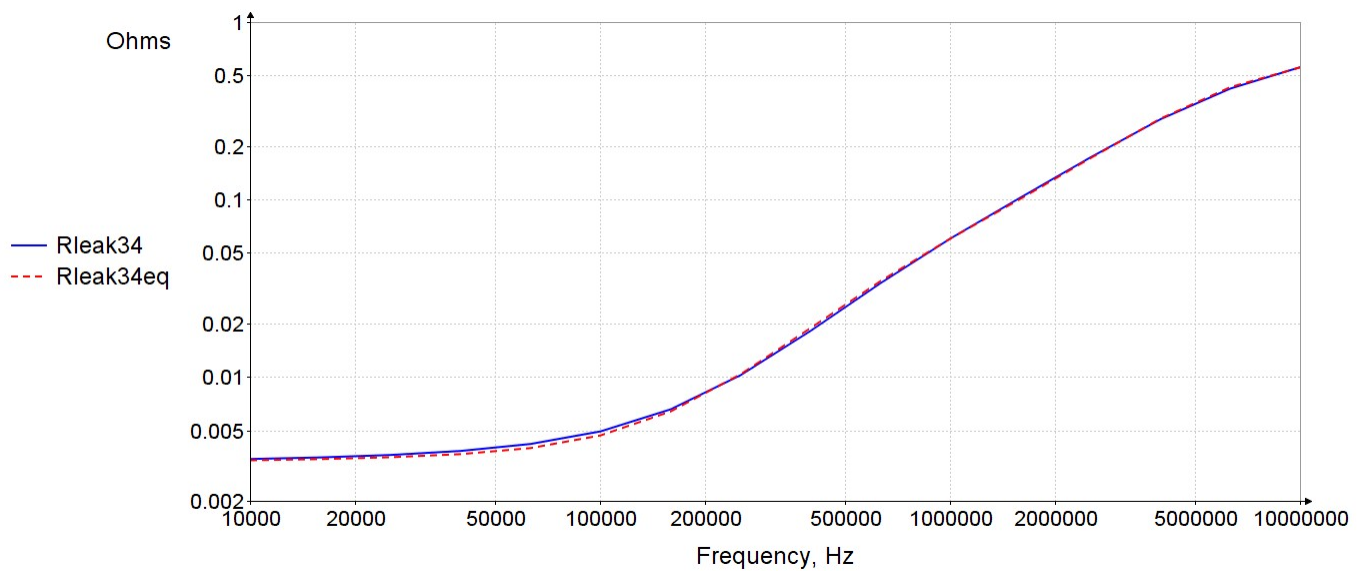
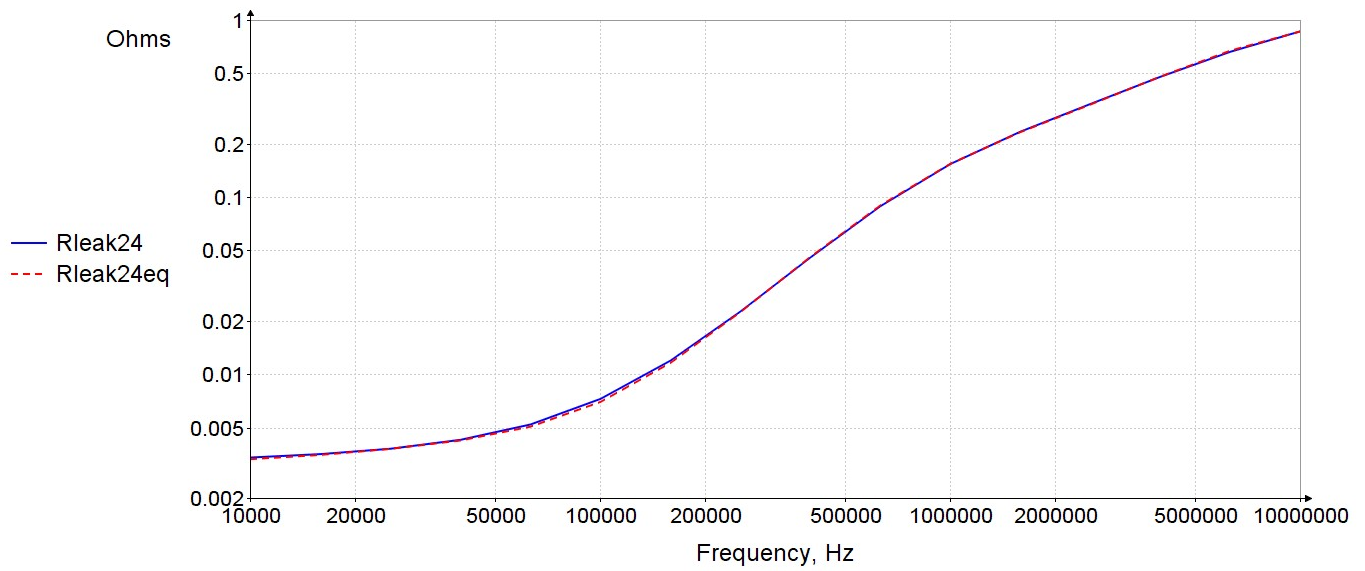
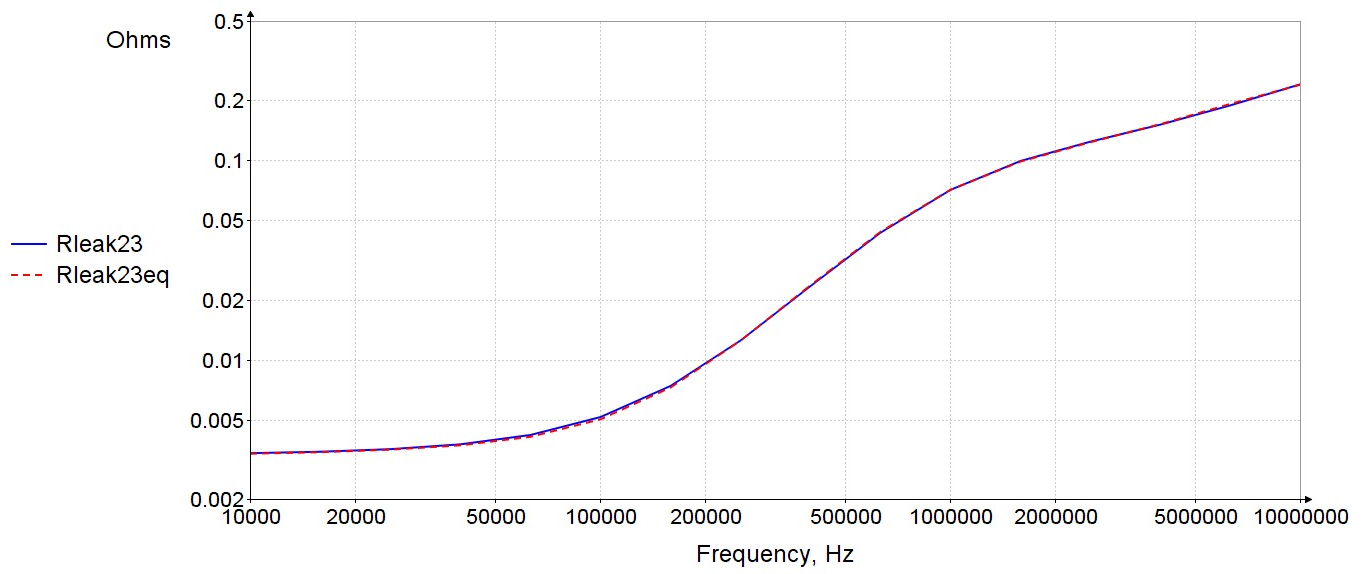


Fig. 18b. FEA and Equivalent Circuit leakage resistances.

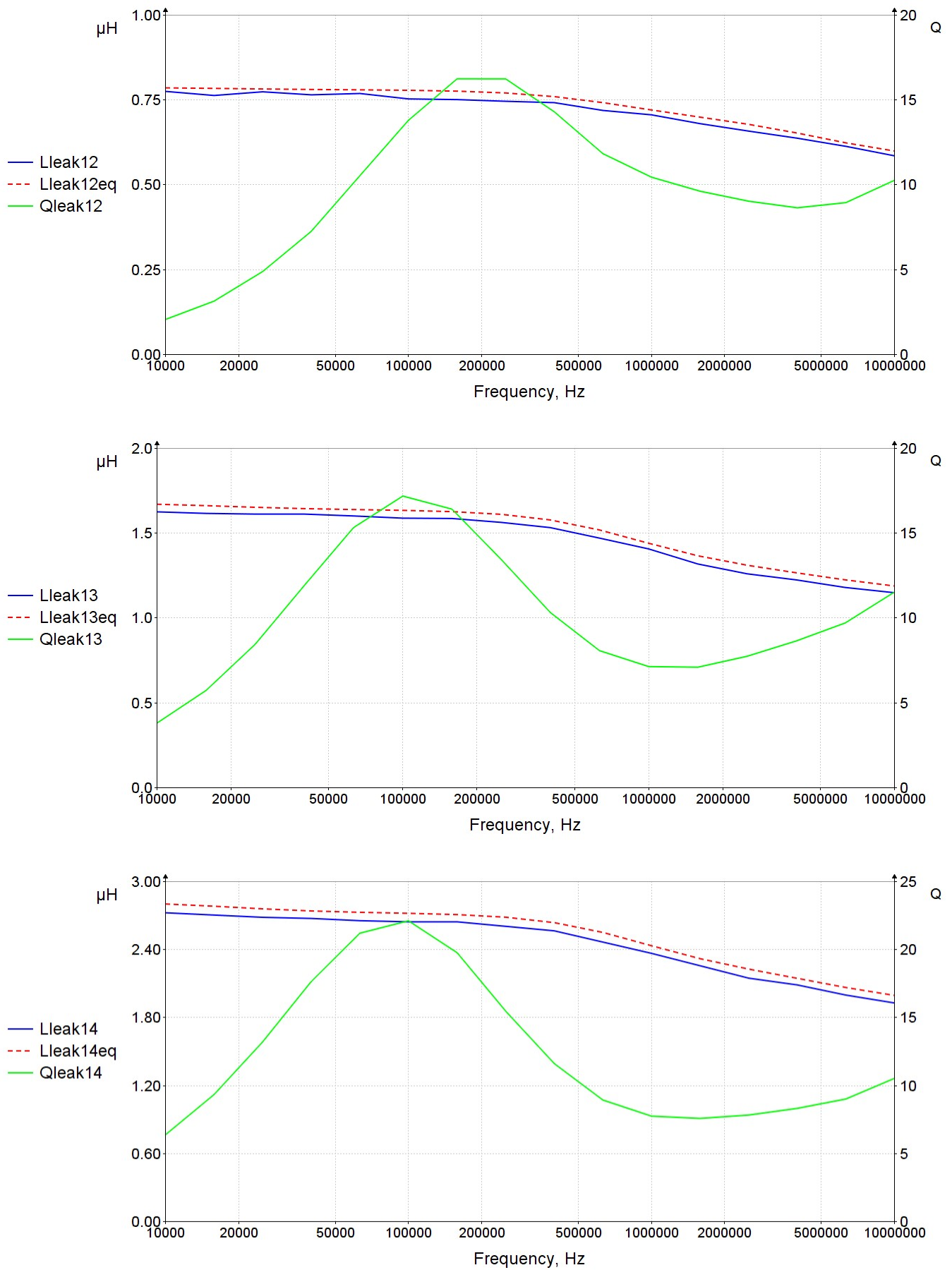


Fig. 19a. FEA and Equivalent Circuit leakage inductances.

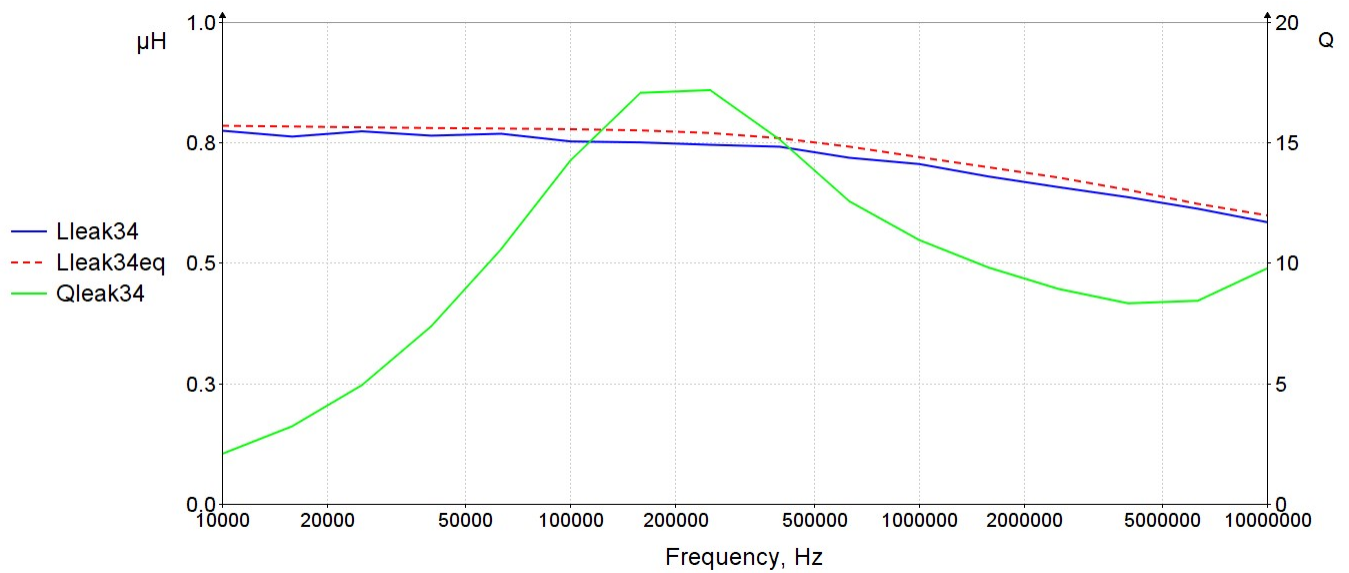
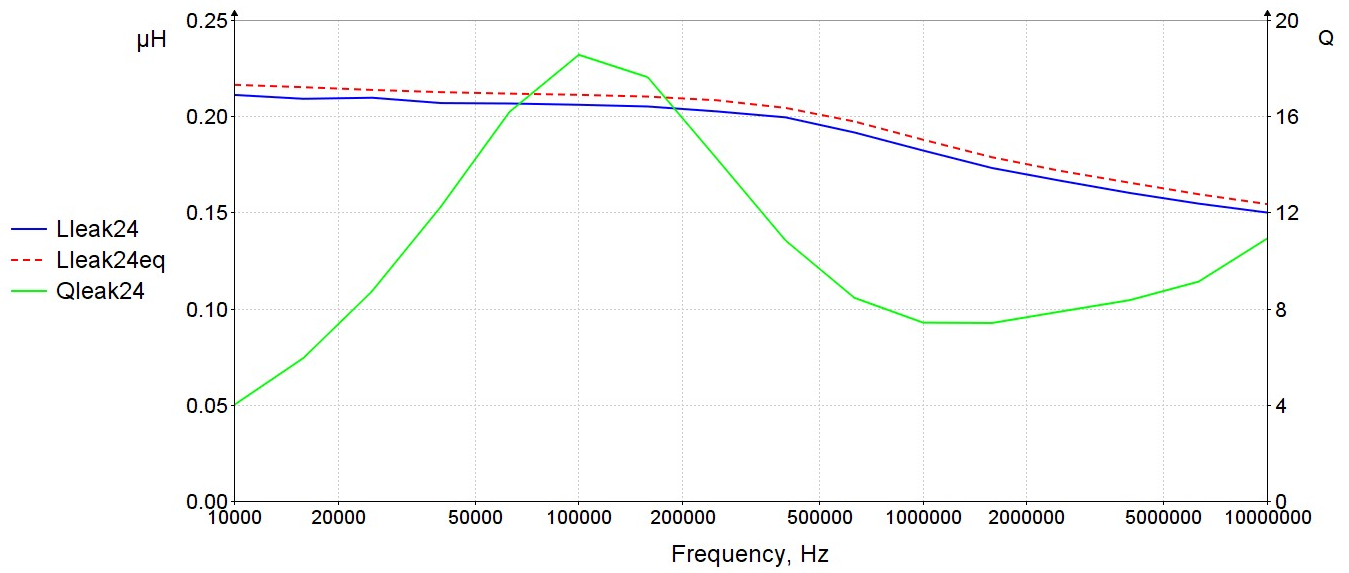
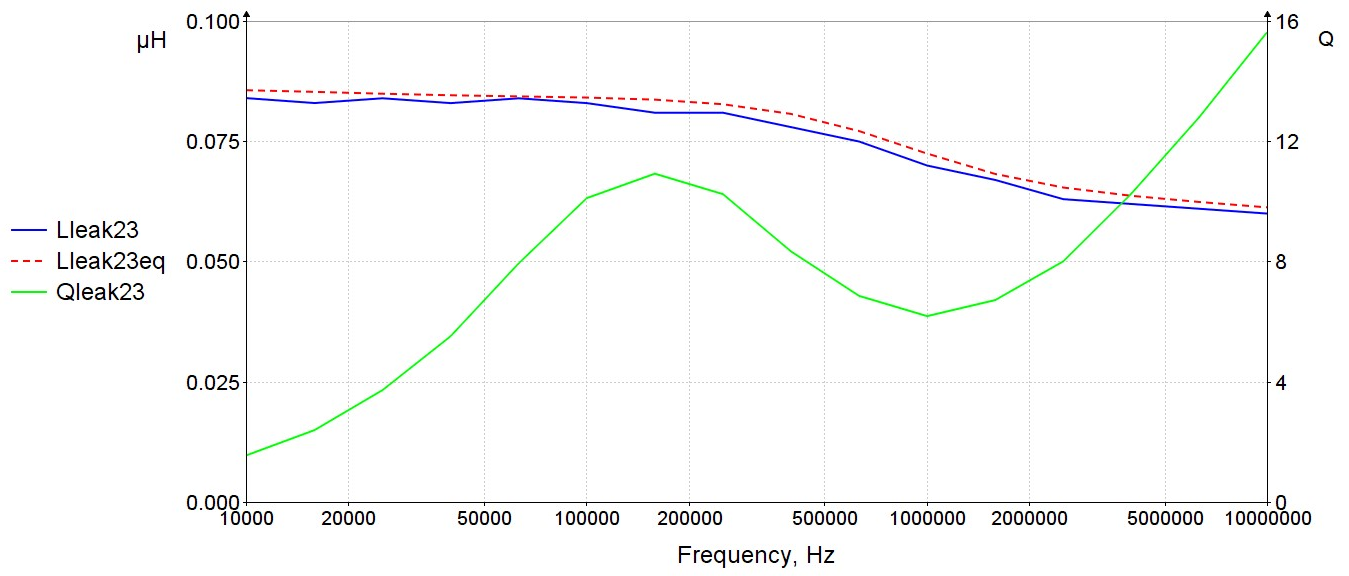


Fig. 19b. FEA and Equivalent Circuit leakage inductances.

References

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<http://ieeexplore.ieee.org/document/847246/>

- [2] B. L. Hesterman, E. E. Mombello and K. Moller, "Discussion of "New power transformer model for the calculation of electromagnetic resonant transient phenomena including frequency-dependent losses" [Closure to discussion]," IEEE Transactions on Power Delivery, vol. 15, No. no. 4, pp. 1320-1323, Oct. 2000
<http://ieeexplore.ieee.org/document/847246/>

- [3] Yilmaz Tokad and Myril B. Reed, "Criteria and Tests for Realizability of the Inductance Matrix," Trans. AIEE, Part I, Communications and Electronics, Vol. 78, Jan. 1960, pp. 924-926
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- [4] James Spreen, "Electrical terminal representation of conductor loss in transformers," IEEE Transactions on Power Electronics, vol. 5, No. 4, Oct 1990, pp. 424-429.
<http://ieeexplore.ieee.org/document/60685/>

Calculate strings for exporting the Lb and Rb values to LTspice.

$$paramLB := \left\| \begin{array}{l} STR_{1,1} \leftarrow \text{"param "} \\ \text{for } m \in 2 \dots \text{rows}(Lb) \\ \quad \left\| STR_{m,1} \leftarrow \text{"+"} \right\| \\ \quad STR \end{array} \right\|$$

$$LBnum := \left\| \begin{array}{l} \text{for } m \in 1 \dots \text{rows}(Lb) \\ \quad \left\| STR_m \leftarrow \text{concat}(\text{"Lb"}, \text{num2str}(m), \text{"="}) \right\| \\ \quad STR \end{array} \right\|$$

$$LB := \left\| \begin{array}{l} \text{for } m \in 1 \dots \text{rows}(Lb) \\ \quad \left\| STR_m \leftarrow \text{concat} \left(paramLB_m, LBnum_m, \text{num2str} \left(\frac{Lb_{m,m}}{\mathbf{H}} \right) \right) \right\| \\ \quad STR \end{array} \right\|$$

$$paramRB := \left\| \begin{array}{l} STR_{1,1} \leftarrow \text{"param "} \\ \text{for } m \in 2 \dots \text{rows}(Rb) \\ \quad \left\| STR_{m,1} \leftarrow \text{"+"} \right\| \\ \quad STR \end{array} \right\|$$

$$RBnum := \left\| \begin{array}{l} \text{for } m \in 1 \dots \text{rows}(Rb) \\ \quad \left\| STR_m \leftarrow \text{concat}(\text{"Rb"}, \text{num2str}(m), \text{"="}) \right\| \\ \quad STR \end{array} \right\|$$

$$RB := \left\| \begin{array}{l} \text{for } m \in 1 \dots \text{rows}(Rb) \\ \quad \left\| STR_m \leftarrow \text{concat} \left(paramRB_m, RBnum_m, \text{num2str} \left(\frac{Rb_{m,m}}{\mathbf{\Omega}} \right) \right) \right\| \\ \quad STR \end{array} \right\|$$

Calculate strings for exporting the RA, LA and KA values.

$$paramRA := \left\| \begin{array}{l} STR_{1,1} \leftarrow \text{"param"} \\ \text{for } m \in 2 \dots \text{rows}(R_A) \\ \left\| \begin{array}{l} STR_{m,1} \leftarrow \text{"+"} \end{array} \right\| \\ STR \end{array} \right\|$$

$$RAnum := \left\| \begin{array}{l} a \leftarrow 1 \\ \text{for } m \in 1 \dots N \\ \left\| \begin{array}{l} \text{for } n \in 1 \dots r \\ \left\| \begin{array}{l} STR_a \leftarrow \text{concat}(\text{"RA"}, \text{num2str}(m), \text{num2str}(n), \text{"="}) \\ a \leftarrow a + 1 \end{array} \right\| \end{array} \right\| \\ STR \end{array} \right\|$$

$$RA := \left\| \begin{array}{l} \text{for } m \in 1 \dots \text{rows}(R_A) \\ \left\| \begin{array}{l} STR_m \leftarrow \text{concat}\left(paramRA_m, RAnum_m, \text{num2str}\left(\frac{R_{A_m}}{\Omega}\right)\right) \end{array} \right\| \\ STR \end{array} \right\|$$

$$LAnum := \left\| \begin{array}{l} a \leftarrow 1 \\ \text{for } row \in 1 \dots N \\ \left\| \begin{array}{l} \text{for } col \in 1 \dots N \\ \left\| \begin{array}{l} \text{for } \kappa \in 1 \dots r \\ \left\| \begin{array}{l} STR_a \leftarrow \text{concat}(\text{num2str}(col), \text{num2str}(\kappa)) \\ a \leftarrow a + 1 \end{array} \right\| \end{array} \right\| \end{array} \right\| \\ STR \end{array} \right\|$$

$$KA := \left\| \begin{array}{l} a \leftarrow 1 \\ Cols \leftarrow \text{rows}(L_A) \\ \text{for } row \in 1 \dots N \\ \left\| \begin{array}{l} \text{for } col \in 1 \dots Cols \\ \left\| \begin{array}{l} STR_a \leftarrow \text{concat}(\text{"KA"}, \text{num2str}(a), \text{"Lb"}, \text{num2str}(row), \text{"LA"}, LAnum_a, \text{" "}, \text{num2str}(k_{A_a})) \\ a \leftarrow a + 1 \end{array} \right\| \end{array} \right\| \\ STR \end{array} \right\|$$

Calculate string for exporting the Kb values.

```

KB :=
  a ← 1
  for row ∈ 1 .. N
    for col ∈ row .. N
      if row ≠ col
        STRa ← concat ("Kb", num2str(a), " Lb", num2str(row), " Lb", num2str(col), ",", num2str(Kbrow,col))
        a ← a + 1
  STR

```

Combine the strings of model parameters for exporting.

```
XFMR_Params := stack(LB, RB, RA, KA, KB)
```

Convert each string to it's binary representation using str2vec, and add a CR=13 and LF=10 at the end of each string.

ORIGIN = 1

```
rowCount := rows(XFMR_Params) = 74
```

```
indices := ORIGIN .. (rowCount - 1 + ORIGIN)
```

```

XFMR_Bin :=
  resultIndex ← ORIGIN
  for rowIndex ∈ indices
    row ← str2vec(XFMR_ParamsrowIndex)
    for colIndex ∈ ORIGIN .. length(row) - 1 + ORIGIN
      resultresultIndex ← rowcolIndex
      resultIndex ← resultIndex + 1
    resultresultIndex ← 13
    resultIndex ← resultIndex + 1
    resultresultIndex ← 10
    resultIndex ← resultIndex + 1
  result

```

```
WRITEBIN("ETD49-25-16_12-4-4-12T.txt", "byte", 0, XFMR_Bin) = 0
```