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Title

R2: LLC CONVERTER — TRANSFORMER DESIGN

Course Name

EE-365 Power Electronics

Keywords

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DESIGN SPECIFICATIONS AND CONSTRAINTS

The second part of the project deals with the design and realization of the magnetic components (i.e. the transformer and the resonant inductor), according to specifications and requirements from Part 1. Fill out Table 1 with the parameters assigned to your group and calculated in the previous Report. Since, for all the groups, the range of the converter's operating frequencies can vary from 50 kHz to 400 kHz, ferrite was chosen as a core material. Thereby, the N87 ferrite material (datasheet pdf) is considered.

Be aware that you need to design the transformer so that its magnetizing inductance matches the L_m needed for your LLC Converter. You are not required to match the leakage inductance of the transformer to your L_r since it will be possible to add an additional external inductor to obtain the needed value. Therefore, the suggested design drives are: matching the needed value of L_m with the magnetizing inductance, and obtaining a leakage inductance lower or equal than the desired L_r (it will be possible to add external inductance to increase the total inductance value to match the desired one, while it will nor be possible to decrease it).

To successfully complete the second part of the project, it is essential to go through the corresponding lecture slides before starting to work on the report. To provide your answers and explanations, use the framed boxes below each question. For the questions where no box for explanations is provided, it is sufficient to only write the solution to the question, without providing any additional reasoning. Consider that this design process is iterative and you will need to go back and rethink your previous decisions whenever you will find out that some constraints are broken or that they lead to unfeasible or undesired operating conditions. You do not need to report every iteration nor give written track of all the iterations. Report only your final design choices and take care of checking that they comply to all the constraints given in the previous and following steps.

Table 1 Given parameters and design requirements for the LLC converter transformer and resonant inductor. ***Note:*** While filling the table consider the different operating condition analyzed in Report 1 and only include here the highest value for current peak and rms values.

Property	Value	Unit
f_{res}	385	kHz
f_{min}	270	kHz
V_{max}	50	V
V_{min}	40	V
P_{out}	50	W
$I_{\mathrm{Lr,peak}}$	4.76	A
$I_{\mathrm{Lr,rms}}$	3.28	A
$I_{\mathrm{D,rms}}$	1.78	A
n	1.041	-
L_{m}	6.09	μH
L_{r}	1.52	μH
ΔT_{goal}	< 50	K

Note: The current and inductor values do not correspond to our values in Report 1 because there was an error in calculations which changed these values slightly. The new values have a difference of less than 10% from the old values.

Q1: MAXIMAL VALUE FOR THE PEAK FLUX DENSITY

To avoid core saturation, the target peak flux density must be constrained to a value well below the saturation flux density value of the core material. The magnetization curves of the available core materials N87 datasheet. Constrain the maximal value of the peak flux density $B_{pk,max}$ well below the saturation flux density value of these core materials. This is a trade-off between the use of the core and core losses.

$B_{\mathrm{pk,max}}$ = 0.35 T

/ 2 pt.

Q2: ESTIMATION OF LOSS COEFFICIENT

To estimate core loss coefficient is possible to use empirical formula derived from Steinmetz equation and given in Equation 1. For the selected material you can use $\alpha = 1.5$ and density $D = 0.00485 kg/cm^3$. Notice that the losses depend of frequency and that the design should consider the worst case. Reflect on which operating frequency would represent the worst case for core losses and calculate the worst case loss coefficient using the given formula

$$K_{fe} = 0.262 \cdot 10^{-3} \cdot f^{\alpha} \cdot D \tag{1}$$

$f_{worst-case}$ = 385000 Hz	K_{fe} = 303.55 $W/T^{\beta}cm^3$	/ 2 pt.

Q3: CALCULATION OF VOLT-SECOND STRESS

Volt-second stress is the integral of the primary voltage waveform over the positive half cycle. You can assume primary voltage in the positive half cycle to be equal to input voltage (constant). Evaluate the volt-second stress in different operating conditions (e.g. $V_{min} - f_{min}$ and $V_{max} - f_{res}$) and report here the worst case condition (the highest value).

The primary voltage waveform is a square wave so the area of the positive half cycle is:

$$A = \lambda_{fmin} = V \times \frac{T}{2} = V \times \frac{1}{2f} = 40\,[\mathrm{V}] \times \frac{1}{2 \times 270\,000\,[\mathrm{Hz}]} = 7.4074 \times 10^{-5}\,[\mathrm{V-sec}]$$

$$\lambda_{fmax} = V \times \frac{T}{2} = V \times \frac{1}{2f} = 6.49 \times 10^{-5}\,[\mathrm{V-sec}]$$

In our case the worst case condition for the volt-second stress occurs with $V_{min} - f_{min}$.

λ = 7.41e-5 V-sec	/ 2 pt.

Q4: CALCULATION OF TOTAL CURRENT STRESS

As explained in the slides, calculate your total current stress. Be aware that your transformer is composed by three wingdings, I_{Lr} is your primary current and I_D is the current in each of your secondaries.

I_{tot} = 6.70 A	/ 1 pt.

Q5: ESTIMATION OF THE WINDOW UTILIZATION FACTOR

The core window area is besides the winding, also consumed by non-conductive materials. Make an estimation of the window utilization factor K_u, also known as the fill factor, to start your design. Be aware that this is only a first estimate and a reference value for yourself, throughout the process and once the core sample is wound you will be able to improve this estimate for the next design iteration.

K_u = 0.5	/ 1 pt.

Q6: ESTIMATION OF LOSSES BUDGET

Set a reasonable target efficiency for your design and calculate your allowed losses P_{tot} considering the nominal output power. Be aware that this is only a first estimate and you will be able to improve it for the next iterations.

Choosing an efficiency of 95%, the allowed power losses can be calculated as follows.

$$P_{tot} = \frac{P_{out}}{0.95} - P_{out} = \frac{50\,[\mathrm{V}]}{0.95} - 50\,[\mathrm{V}] = 2.63\,[\mathrm{W}]$$

P_{tot} = 2.63 W	/ 2 pt.

Q7: TARGET CURRENT DENSITY

Unlike lone wires in free-air electric installations and PCB tracks, densely packed multi-layer windings cannot dissipate loss heat just as well with only natural air cooling. It is a trade-off between copper losses respectively temperature rise and power density. Considering the usual values given in the slides, select a certain current density constraint to start your design. While you go through the following steps of the process or once you prototype your first design, you can adjust this constraint and re-iterate your design to optimize it in one of the directions. Note that due to discrete wire gauges it will not be possible to exactly match the selected value.

$J_w^* = 400 \quad A/cm^2$ / 1 pt.

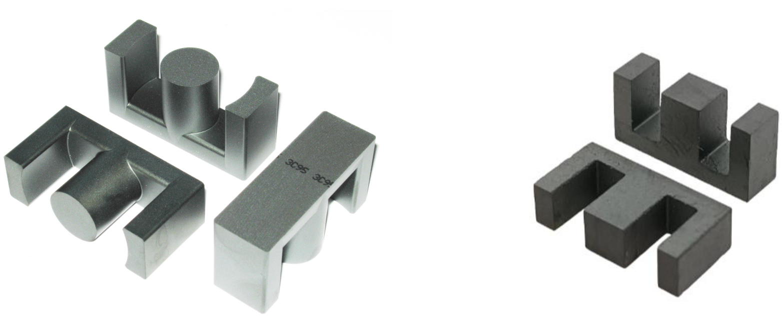
CORE SELECTION WITH KG METHOD

As suggested in the slides and in literature one of the most commonly used methods to design a transformer is the K_g method, modified for AC applications to take into account both core and copper losses and to minimize them. This method is usually refered to as K_{gfe} method. (More details can be found in the slides or in the book *Fundamentals of Power Electronics* by Erickson and Maksimovic, Springer)

Magnetic core manufacturers provide a vast variety of core shapes and sizes. In this course, a preselection of suitable cores is given in Table 2. The geometrical K_{gfe} factor for each of the available core is also calculate considering the geometrical dimension given in the databooks and $\beta = 2.7$ as is usually done for ferrites. You are requested to choose one of the available cores for your design.

Table 2 Available core materials and core shapes.

Core shape	N87 core	Coil former	Yoke	K_{gfe} $[cm^5]$
E20/10/6	B66311G0000X187	B66206B1110T001	B66206A2010X000	0.0022
E25/13/7	B66317G0000X187	B66208X1010T001	B66208A2010X000	0.0042
E30/15/7	B66319G0000X187	B66232B1114T001	B66232A2010X000	0.0056
E32/16/9	B66229G0000X187	B66230A1114T001	B66230A2010X000	0.0089
ETD34/17/11	B66361G0000X187	B66362X1014T001	B66362A2000X000	0.0114
ETD39/20/13	B66363G0000X187	B66364B1016T001	B66364A2000X000	0.0200
ETD44/22/15	B66365G0000X187	B66366B1018T001	B66366A2000X000	0.0300



(a) ETD (b) EE

Figure 1 Core shapes

Q8: MINIMUM K_{gfe}

Using the values calculated and estimated in previous section, and considering $\beta = 2.7$, calculate the minimum required K_{gfe} needed in your specific conditions. Copper resistivity can be considered to be $\rho = 1.724 \cdot 10^{-6} \Omega cm$. ***Note:*** while performing the calculations be careful to use the correct units (e.g. dimensions in cm or cm^2, currents in A, power in W)

The minimum required K_{gfe} needed for our specific conditions can be calculated as follows.

$$K_{\text{gfe}} \geq \frac{\rho\lambda_1^2 I_{tot}^2 K_{fe}^{(2/\beta)}}{4K_u P_{tot}^{((\beta+2)/\beta)}} x10^8$$

$$= \frac{1.724\times10^{-6}[\Omega cm]\times(7.4074\times10^{-5}\,[\text{V}-\text{sec}])^2\times(6.6998\,[\text{A}])^2\times303.5527[W/T^\beta cm^3]^{(2/2.7)}}{4\times0.5\times2.6316\,[\text{W}]^{((2.7+2)/2.7)}}\times10^8$$

$$= 2.72\times10^{-4}\,[\text{cm}^5]$$

$K_{\text{gfe}} = 2.72\times10^{-4}$ cm^5

/ 3 pt.

Q9: CHOICE OF CORE FROM THE TABLE OF SELECTED MATERIALS

Indicate the core shape from Table 2 that you want to use for your design, considering the needed minimum K_{gfe}. As first attempt, you can choose whatever core that has a K_{gfe} bigger than the needed one, bigger cores will reduce the power density of your converter. Be aware that your core size also has an influence on current density and losses. These are going to be analyzed in the following questions. It is very likely that you will need to iterate your answer on this question to meet all the constraints.

Core shape: E32/16/9

/ 3 pt.

Q10: CHECK ON THE FLUX DENSITY

Using the formula presented in the slides, check that the expected ΔB (peak ac flux density, peak-to-average) in your operating conditions is never exceeding the $B_{\text{pk,max}}$ selected in Q1. This will ensure that saturation never occurs in the expected operating conditions. Information on the geometrical dimensions of the selected cores can be found in the provided core databook (i.e. Ferroxcube - pdf here)

The following formula can be used to check on the flux density.

$$\Delta B = \left(\frac{\rho\lambda_1^2 I_{tot}(MLT)}{2K_u W_A A_c^3 l_m \beta K_{fe}}\right)^{\left(\frac{1}{\beta+2}\right)} = \left(\frac{1.724e-6[\Omega cm]\times7.4074\times10^{-5}\,[\text{V}-\text{sec}]\times6.6998\,[\text{A}]\times5.6\,[\text{cm}]}{2\times0.5\times0.8\,[\text{cm}^2]\times0.6\,[\text{cm}^2]^3\times6.7\,[\text{cm}]\times2.7\times303.5527[W/T^\beta cm^3]}\right) = 0.0305\,[\text{T}]$$

As seen, the expected ΔB value of 0.0305 T is less than the $B_{\text{pk,max}}$ of 0.35 T.

ΔB: 0.0305 T

/ 2 pt.

Q11: CALCULATION OF NEEDED NUMBER OF TURNS ACCORDING TO K_{gfe}

Using the formula presented in the slides, calculate the desired number of turns on the primary side to minimize the total losses. Then, considering the transformer ratio required for your design, calculate the number of turns needed for your secondaries. Make sure that each winding is composed by a integer number of turns. ***Note:*** while performing the calculations be careful to use the correct units (e.g. dimensions in cm or cm^2, flux density in T)

The primary number of turns can be calculated as follows.

$$N_1 = \frac{\lambda_1}{2\Delta B A_c} \times 10^4 = \frac{7.4074 \times 10^{-5}\,[\mathrm{V-sec}]}{2 \times 0.0305\,[\mathrm{T}] \times 0.6\,[\mathrm{cm}^2]} \times 10^4 = 20.2081 \approx 21$$

However, due to later calculations involving the selected wires and air gap manufacturability, a value of $N_1 = 9$ is chosen instead. Then, $N_{2,1} = N_{2,2} = \frac{N_1}{n} = \frac{9}{1.041} = 8.64 \approx 9$ turns as well. Also, to verify if this value is possible we check: $\Delta B = 0.049 < \Delta B_{max}$

$N_1 = 9$ | $N_{2,1} = 9$ | $N_{2,2} = 9$ | $n = 1.041$ | / 3 pt.

WIRE SELECTION

The following step in the transformer design is to select a suitable wire. Different aspects needs to be considered in this choice. Increasing the wire cross section would reduce the resistance, but at the same time would lead to an higher utilization factor or to the need for a bigger core. In addition, operating condition are set in the range $50 - 400kHz$, this leads to a significant weight of skin effect on the effective AC resistance. In the following tables, you will find a list of the materials available.

Table 3 Available magnet wires.

Wire number	M1	M2	M3	M4	M5	M6	M7
Conductor diameter [mm]	0.65	0.9	1.0	1.2	1.54	1.6	1.8

Table 4 Available Litz wires (single conductor diameter 0.2mm).

Wire number	L1	L2	L3	L4
Number of strands	25	35	45	80
Total Conductive Area [mm^2]	0.78	1.10	1.41	2.51
External Diameter [mm]	1.53	1.8	2.06	2.8

Q12: SKIN DEPTH

To develop a feeling of the specific weight of skin effect on your design evaluate the skin depth at your minimum and maximum operating frequency.

The following formula can be used to determine the skin depth at our minimum and maximum operating frequencies.

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} = \sqrt{\frac{2\rho}{2\pi f \mu_0 \mu}}$$

At f_{min}:

$$\delta = \sqrt{\frac{2\rho}{2\pi f \mu_0 \mu}} = \sqrt{\frac{2 \times 1.724 \times 10^{-8}\,[\mathrm{m}]}{2\pi \times 270\,000\,[\mathrm{Hz}] \times 1.2566 \times 10^{-6}\,[\mathrm{H/m}] \times 1}} = 1.2718 \times 10^{-4}\,[\mathrm{m}] = 0.127\,18\,[\mathrm{mm}]$$

At f_{max}:

$$\delta = \sqrt{\frac{2\rho}{2\pi f \mu_0 \mu}} = \sqrt{\frac{2 \times 1.724 \times 10^{-8}\,[\mathrm{m}]}{2\pi \times 385\,000\,[\mathrm{Hz}] \times 1.2566 \times 10^{-6}\,[\mathrm{H/m}] \times 1}} = 1.065 \times 10^{-4}\,[\mathrm{m}] = 0.1065\,[\mathrm{mm}]$$

$\delta_{\mathrm{f,min}} = 0.127$ mm	$\delta_{\mathrm{f,max}} = 0.107$ mm	/ 3 pt.

Q13: CALCULATION OF FRACTION OF WINDOW AREA TO ALLOCATE TO EVERY WINDING

Take into account the rms current expected in each winding, the calculated number of turns and the total current calculated in the first section. Calculate the fraction of window area that should be allocated to each of your three windings.

The following formula can be used to evaluate the fraction of window area allocated to each winding.

$$\alpha_j = \frac{n_j I_j}{n_1 I_{tot}}$$

For α_1:

$$\alpha_1 = \frac{n_1 I_1}{n_1 I_{tot}} = \frac{9 \times 3.28\,[\mathrm{A}]}{9 \times 6.6998\,[\mathrm{A}]} = 0.4896$$

For $\alpha_{2,1}$ and $\alpha_{2,2}$:

$$\alpha_{2,1} = \alpha_{2,2} = \frac{n_2 I_2}{n_1 I_{tot}} = \frac{9 \times 1.78\,[\mathrm{A}]}{9 \times 6.6998\,[\mathrm{A}]} = 0.2657$$

$\alpha_1 = 0.49$	$\alpha_{2,1} = 0.27$	$\alpha_{2,2} = 0.27$	/ 2 pt.

Q14: CALCULATION OF MAXIMUM WIRE AREA

Considering the dimensions of the selected core and the allocated fraction for each wire winding, calculate the maximum wire area that would fit in the available space. Note that this represent the total conductor area.

The maximum wire area can be calculated using the following formula.

$$A_{wj} \leq \frac{\alpha_j K_u W_A}{n_1}$$

For $A_{w1,max}$:

$$A_{w1,max} = \frac{0.4896 \times 0.5 \times 80\,[\mathrm{mm}^2]}{9} = 2.6382\,[\mathrm{mm}^2]$$

For $A_{w21,max}$ and $A_{w22,max}$:

$$A_{w12,max} = A_{w22,max} = \frac{0.2657 \times 0.5 \times 80\,[\mathrm{mm}^2]}{9} = 1.4317\,[\mathrm{mm}^2]$$

$A_{\mathrm{w1,max}} = 2.64$ mm^2	$A_{\mathrm{w21,max}} = 1.43$ mm^2	$A_{\mathrm{w22,max}} = 1.43$ mm^2	/ 2 pt.

Q15: CALCULATION OF NEEDED CONDUCTOR AREA

Consider your target current density defined in Q7 and the rms current expected in your windings according to simulation performed in Report 1. Evaluate the Total Conductive area (A_{TC}) needed to satisfy your requirement. Compare this area with the maximum available in the core you selected (see the answer form previous question). If the available area (Q14) is smaller than the needed one (Q15), go back to Q9 and select a bigger core. Note that if the needed area is only slightly bigger than the maximum available one, you can choose to proceed with your selected core, although pay special attention to utilization factor control (Q23) to make sure that your design is still feasible. Be aware that core selection will also be influenced by next question answers, consider to reiterate your design taking into account also information and choices taken in Q16.

Total conductive area can be conducted as follows.

$$A_{TC} = \frac{I_{rms}}{J_w}$$

For $A_{TC,1}$:

$$A_{TC,1} = \frac{I_{lr,rms}}{J_w} = \frac{3.29\,[\mathrm{A}]}{4\,[\mathrm{mm}^2]} = 0.82\,[\mathrm{mm}^2]$$

For $A_{TC,2}$ and $A_{TC,3}$:

$$A_{TC,2} = A_{TC,3} = \frac{I_{d,rms}}{J_w} = \frac{1.78\,[\mathrm{A}]}{4\,[\mathrm{mm}^2]} = 0.445\,[\mathrm{mm}^2]$$

As seen, the available area calculated in Q14 are greater than the needed areas calculated in Q15, as required.

$A_{\mathrm{TC},1} = 0.82$ mm^2	$A_{\mathrm{TC},2} = 0.45$ mm^2	$A_{\mathrm{TC},3} = 0.45$ mm^2	/ 3 pt.

Q16: WIRE SELECTION

Now consider the available wires in Table 3 and 4. For Magnet Wires (Table 3) you can consider Total Conductive area as the total area of the wire, for Litz Wires (Table 4) the total conductive area is given in the Table.
Once again consider target current density (Q7) and expected rms current (Report 1), in addition use expected needed total conductor area (Q15) as a guideline. Select the wire that is most suitable for your case. Note that due to the limited number of wire choices available you may not be able to realize exactly your target current density, choose the closest possible value considering the wire technology of your choice. Check that the area needed for your selected winding is lower than the maximum available one (Q14), otherwise reconsider your core choice (Q9). Note that your technology choice (Magnet or Litz wire) will effect your losses and the size of your transformer, you may want to reconsider your choice after calculating AC losses in Q25. In your reply, indicate the label given in the table to the wire of your choice.

Selection of wire 1: M3 was chosen for wire one because its conductor area was determined to be $0.79\,\mathrm{mm}^2$, which is the closest value to $A_{TC,1}$ calculated in Q15, with a difference of $0.034\,\mathrm{mm}^2$ that is assumed to be negligible. Additionally, the current density using M3 is $J_{w,1} = \frac{I_{lr,rms}}{A} = \frac{3.28\,[\mathrm{A}]}{0.7854\,[\mathrm{mm}^2]} = 4.1762\,[\mathrm{A/mm}^2]$, which is the closest attainable value to the target current density of $4\,[\mathrm{A/mm}^2]$.

Selection of wires 2,1 and 2,2: M2 was chosen as its conductor area was determined to be $0.6362\,\mathrm{mm}^2$, slightly greater than the required area of $0.45\,\mathrm{mm}^2$ calculated in Q15. The current density using M2 is $J_{w,2} = \frac{I_{d,rms}}{A} = \frac{1.78\,[\mathrm{A}]}{0.6362\,[\mathrm{mm}^2]} = 2.798\,[\mathrm{A/mm}^2]$, which is also the closest value attainable to the target current density of $4\,[\mathrm{A/mm}^2]$.

Selected wire 1: M3	$A_{\mathrm{w1,selected}} = 0.79$ mm^2	$A_{\mathrm{TC,1,sel}} = 0.82$ mm^2	$J_{\mathrm{w1,selected}} = 4.18$ A/mm^2	Selected wire 2,1: M2
$A_{\mathrm{w21,selected}} = 0.64$ mm^2	$A_{\mathrm{TC,21,sel}} = 0.45$ mm^2	$J_{\mathrm{w21,result}} = 2.80$ A/mm^2		
Selected wire 2,2: M2	$A_{\mathrm{w22,selected}} = 0.64$ mm^2	$A_{\mathrm{TC,22,sel}} = 0.45$ mm^2	$J_{\mathrm{w22,selected}} = 2.80$ A/mm^2	/ 4 pt.

CALCULATION OF AIR GAP LENGTH

Q17: AIR GAP CALCULATION

As defined in the introduction of this report, your objective is to design the magnetizing inductance of your transformer to match the needed magnetizing inductance for your design. The magnetizing inductance is depending on the number of turns and on the reluctance of the magnetic path. Once the number of turns, the material and the core shape have been fixed, one degree of freedom is left in the air gap length. Calculate the total air gap needed in your design and provide your reasoning.

The air gap can be calculated as follows.

$$l_{g,tot} = \frac{N^2 \mu_0 A_c}{L_m} \times 10^{-4} = \frac{9^2 \times 1.2566 \times 10^{-6}\,[\mathrm{H/m}] \times 0.97\,[\mathrm{cm}^2]}{6.09 \times 10^{-6}\,[\mathrm{H}]} \times 10^{-4} = 0.0014\,[\mathrm{cm}]$$

$l_{\mathrm{g,tot}}$ = 1.35 *mm*

/ 4 pt.

Q18: AIR GAP MANUFACTURABILITY

To ensure easy manufacturability, the air gap will be realized inserting certain number of layers of Kapton tape (thickness of one layer 65μm). Remember that the gap will be inevitably present two times in the magnetic path (tape will be placed in the two external legs of the core), therefore adjust the needed value and calculate the number of Kapton tape needed for each side. Consider that only an integer number of layers can be chosen, calculate the total manufactured gap.

The number of Kapton layers required per side is calculated as follows.

$$N_{Kapton} = \frac{l_{g,tot}}{2 \times 65[\mu m]} = \frac{0.6768\,[\mathrm{mm}]}{65[\mu m]} \approx 10$$

The new air gap value is therefore:

$$l_{g,tot,real} = N_{Kapton} \times 0.065\,[\mathrm{mm}] \times 2 = 10 \times 0.065\,[\mathrm{mm}] \times 2 = 1.30\,[\mathrm{mm}]$$

Number of needed Kapton layers per side = 10

$l_{\mathrm{g,tot,real}}$ = 1.30 *mm*

/ 3 pt.

ADJUSTMENTS CONSIDERING THE FRINGING FLUX

Q19: FRINGING FLUX FACTOR

Due to the introduction of the air gap, it is not possible to consider an ideal magnetic flux distribution, but it is essential to consider that magnetic flux spreads out into the surrounding medium, in proximity of the air gap. This effect modifies the magnetizing inductance value. Calculate the fringing flux factor F_{fringe}. Use the winding width value G from the coil former data sheet (Nominal Winding Width in Ferroxcube databook).

The fringing flux factor is:

$$F_{fringe} = 1 + \frac{l_g}{\sqrt{A_c}} \times \ln\left(\frac{2G}{l_g}\right) = 1 + \frac{1.3\,[\mathrm{mm}]}{\sqrt{83\,[\mathrm{mm}^2]}} \times \ln\left(\frac{2 \times 20.2\,[\mathrm{mm}]}{1.3\,[\mathrm{mm}]}\right) = 1.4904$$

G = 20.20 *mm*	F_{fringe} = 1.49	/ 3 pt.

Q20: ADJUSTMENT OF NUMBER OF TURNS DUE TO FRINGING FLUX

Due to the effect of the fringing field the magnetizing inductance value is modified. While keeping the air gap unchanged (equal to the effective one you obtain using a integer number of Kapton tape layers - Q18), recalculate the number of turns needed to obtain your desired L_m. Calculate $N_{1,\text{new}}$ and adjust the the number of turns of the primary to obtain the desired transformer ratio. Also in this case, make sure that each winding is composed by a discrete number of turns.

For $N_{1,new}$:

$$N_{1,new} = \sqrt{\frac{L_m}{F_{fringe}} \times \frac{1}{\mu_0 A_c} \times (l_g + \frac{MLT}{\mu})}$$

$$= \sqrt{\frac{6.09 \times 10^{-6}\,[\mathrm{H}]}{1.4904} \times \frac{1}{1.2566 \times 10^{-6}\,[\mathrm{H/m}] \times 0.83 \times 10^{-4}\,[\mathrm{m}^2]} \times (0.0013\,[\mathrm{m}] + \frac{0.06\,[\mathrm{m}]}{2200})} \approx 8$$

For $N_{21,new}$ and $N_{22,new}$:

$$N_{21,new} = N_{22,new} = \frac{N_{1,new}}{n} = \frac{8}{1.041} \approx 8$$

$N_{1,new}$ = 8	$N_{21,new}$ = 8	$N_{22,new}$ = 8	/ 3 pt.

Q21: CHECK ON MAXIMUM FLUX

Using the inverse of the formula you applied in Q11. Calculate the maximum ΔB expected with the newly selected number of turns. Check that this is still below the $B_{\text{pk,max}}$ your selected in Q1 to avoid saturation.

The maximum flux with the newly selected number of turns is:

$$\Delta B_{new} = \frac{\lambda_1}{2 N_1 A_c} \times 10^4 = \frac{7.4074 \times 10^{-5}\,[\mathrm{V-sec}]}{2 \times 8 \times 0.83\,[\mathrm{cm}^2]} \times 10^4 = 0.0558\,[\mathrm{T}]$$

ΔB_{new} = 0.056 T	/ 3 pt.

Q22: EVALUATION OF EXPECTED MAGNETIZING INDUCTANCE VALUE

Compute the final value of the magnetizing inductance using the new number of turns just select. You can use the inverse of the formula you used to compute the number of turns.

The expected magnetizing inductance value is:

$$L_{m,final} = F_{fringe} \times L_m = 1.4904 \times 6.09 \times 10^{-6}\,[\mathrm{H}] = 9.07 \times 10^{-6}\,[\mathrm{H}]$$

This value can be later adjusted by adding Kapton layers assuming the risk of more losses.

$L_{m,final}$ = 9.07 μH

/ 3 pt.

VERIFICATION OF THE DESIGN CONSTRAINTS AND EVALUATION OF LOSSES

Q23: WINDOW UTILIZATION FACTOR

Considering the core and wires you selected, calculate the current window utilization factor $K_{\mathrm{u,real}}$ to verify if the core window area is too occupied, before coming to the practical winding. Compare it with your initial estimate in Q5.

The primary used area is:

$$A_1 = A_{wire,1}N_1 = 0.7854\,[\mathrm{mm}^2] \times 8 = 6.2832\,\mathrm{mm}^2$$

The secondary used area is:

$$A_2 = 2 \times A_{wire,2}N_2 = 2 \times 0.6362\,[\mathrm{mm}^2] \times 8 = 10.1788\,[\mathrm{mm}^2]$$

The total used area is therefore:

$$A_{tot} = A_1 + A_2 = 6.2832\,[\mathrm{mm}^2] + 10.1788\,[\mathrm{mm}^2] = 16.4619\,[\mathrm{mm}^2]$$

The real window utilization factor is therefore:

$$K_{u,real} = \frac{A_{tot}}{W_A} = \frac{16.4619\,[\mathrm{mm}^2]}{97\,[\mathrm{mm}^2]} = 0.1697$$

This factor is less than the initial estimate of $K_u = 0.5$ by 0.3303, which leaves space for any human error in winding.

$K_{\mathrm{u,real}}$ = 0.17

/ 2 pt.

Q24: DC WINDING RESISTANCE

Calculate the DC winding resistance R_L of the designed transformer. Use thereby the MLT (from core datasheet), A_w (from selected wires, use total conductive area) and the resistance per length for copper wire ($\rho = 1.724e - 6\Omega cm$).

The DC winding resistances are as follows.

$$R_{L1} = \frac{\rho n_1(MLT)}{A_{w1}} \times 10^6 = \frac{1.724 \times 10^{-8}\,[\mathrm{m}] \times 8 \times 0.06\,[\mathrm{m}]}{0.7854\,[\mathrm{mm}^2]} \times 10^6 = 0.0105[\Omega]$$

$$R_{L21} = R_{L22} = \frac{\rho n_2(MLT)}{A_{w2}} \times 10^6 = \frac{1.724 \times 10^{-8}\,[\mathrm{m}] \times 8 \times 0.06\,[\mathrm{m}]}{0.6362\,[\mathrm{mm}^2]} \times 10^6 = 0.0130[\Omega]$$

R_{L1} = 0.011 Ω	R_{L21} = 0.013 Ω	R_{L22} = 0.013 Ω	/ 3 pt.

Q25: AC WINDING RESISTANCE

Calculate the AC winding resistance $R_{L,ac}$ only taking into account skin depth, you are allowed to neglect proximity effect and other phenomena. **Note**: skin effect is only effecting your resistance if the radius of each of your isolated conductors is bigger than your skin depth.

As we are only using magnetizing wires, we need to calculate the effective conductive area. From Q12, $\delta_{f,min} = 0.1272\,\text{mm}$. Therefore, the wire area impacted by the skin effect for wire 1 is

$$A_{skin,1} = \pi(\frac{d_{wire,1}}{2} - \delta_{f,min})^2 = \pi(\frac{1\,[\text{mm}]}{2} - 0.1272\,[\text{mm}])^2 = 0.4367\,[\text{mm}^2]$$

The effective conductive area for wire 1 is therefore:

$$A_{eff,1} = A_{wire,1} - A_{skin,1} = 0.7854\,[\text{mm}^2] - 0.4367\,[\text{mm}^2] = 0.3487\,[\text{mm}^2]$$

Finally, the AC winding resistance for wire 1 is:

$$R_{L1,ac} = \frac{\rho n_1(MLT)}{A_{w1}} \times 10^6 = \frac{1.724 \times 10^{-8}\,[\text{m}] \times 8 \times 0.06\,[\text{m}]}{0.3487\,[\text{mm}^2]} \times 10^6 = 0.0237[\Omega]$$

For $R_{L21,ac}$ and $R_{L22,ac}$:

$$A_{skin,2} = \pi(\frac{d_{wire,2}}{2} - \delta_{f,min})^2 = \pi(\frac{0.9\,[\text{mm}]}{2} - 0.1272\,[\text{mm}])^2 = 0.3274\,[\text{mm}^2]$$

$$A_{eff,2} = A_{wire,2} - A_{skin,2} = 0.6362\,[\text{mm}^2] - 0.3274\,[\text{mm}^2] = 0.3088\,[\text{mm}^2]$$

The AC winding resistance for the secondary wires is:

$$R_{L21,ac} = R_{L22,ac} = \frac{\rho n_2(MLT)}{A_{w2}} \times 10^6 = \frac{1.724 \times 10^{-8}\,[\text{m}] \times 8 \times 0.06\,[\text{m}]}{0.3088\,[\text{mm}^2]} \times 10^6 = 0.0268[\Omega]$$

$R_{L1,ac}$ = 0.024 Ω	$R_{L21,ac}$ = 0.027 Ω	$R_{L22,ac}$ = 0.027 Ω	/ 4 pt.

Q26: DC E AC COPPER LOSSES

Calculate the total DC copper losses $P_{\text{Cu,dc}}$ and AC copper losses $P_{\text{Cu,ac}}$, which arise due to the currents flowing through all the windings of the transformer. Perform calculation considering nominal power, both at minimum and maximum input voltage. Calculate the percentage of the nominal output power to which the AC copper losses correspond to.

Using Ohm's law and the corresponding simulated current values for minimum input voltage ($I_{lr,rms,Vmin} = 3.28A$ and $I_{d,rms,Vmin} = 1.78A$) and maximum input voltage ($I_{lr,rms,Vmax} = 2.9A$ and $I_{d,rms,Vmax} = 1.66A$), the DC and AC copper losses for each condition can be calculated as follows.

At minimum input voltage:

$$P_{Cu,ac,Vmin} = I_{lr,rms}^2 R_{ac,1} + 2I_{d,rms}^2 R_{ac,2} = 3.28\,[\text{A}]^2 \times 0.0237[\Omega] + 2 \times 1.78\,[\text{A}]^2 \times 0.0268[\Omega] = 0.4251\,[\text{W}]$$

$$P_{Cu,dc,Vmin} = I_{lr,rms}^2 R_{dc,1} + 2I_{d,rms}^2 R_{dc,2} = 3.28\,[\text{A}]^2 \times 0.0105[\Omega] + 2 \times 1.78\,[\text{A}]^2 \times 0.0130[\Omega] = 0.1958\,[\text{W}]$$

As we only use AC values, for the final calculation only Rac is used, and so the total copper losses at minimum input voltage correspond to $P_{Cu,Vmin} = \frac{0.4251[W]}{50\,[\text{W}]} \times 100\,\% = 0.85\,\%$ of the nominal output power.

At maximum input voltage:

$$P_{Cu,ac,Vmax} = I^2_{lr,rmsVmax}R_{ac,1} + 2I^2_{d,rmsVmax}R_{ac,2} = 2.9\,[\mathrm{A}]^2 \times 0.0237[\Omega] + 2 \times 1.66\,[\mathrm{A}]^2 \times 0.0268[\Omega] = 0.3473\,[\mathrm{W}]$$

$$P_{Cu,dc,Vmax} = I^2_{lr,rmsVmax}R_{dc,1} + 2I^2_{d,rmsVmax}R_{dc,2} = 2.9\,[\mathrm{A}]^2 \times 0.0105[\Omega] + 2 \times 1.66\,[\mathrm{A}]^2 \times 0.0130[\Omega] = 0.1603\,[\mathrm{W}]$$

The total copper losses at maximum input voltage therefore correspond to $P_{Cu,Vmax} = \frac{0.3473[W]}{50\,[W]} \times 100\,\% = 0.69\,\%$ of the nominal output power.

With minimum input voltage: $P_{Cu,dc} =$ 0.1958 W and $P_{Cu,ac} =$ 0.4251 W which corresponds to 0.85 % of the output power.

With maximum input voltage: $P_{Cu,dc} =$ 0.1603 W and $P_{Cu,ac} =$ 0.3473 W which corresponds to 0.69 % of the output power.

/ 3 pt.

Q27: ESTIMATION OF CORE LOSSES

With the help of a core loss density plot provided in the material's data sheet (N87), estimate the core losses P_{core} of the designed transformer. The core volume can be instead found in the core shapes databook (Ferroxcube). Calculate the percentage of the nominal output power to which the core losses correspond to.

From Q21, $\Delta B_{new} = 0.0558\,\mathrm{T}$. Using this value and interpolating from the core loss density plot:

$$P_{core} = P_v V_e = 180\,000\,[\mathrm{W}] \times 0.618 \times 10^{-5}\,[\mathrm{m}^3] = 1.1124\,[\mathrm{W}]$$

The percentage of the nominal output power to which the core losses correspond to is $\frac{1.1124\,[W]}{50\,[W]} \times 100\,\% = 2.22\,\%$

$P_{\text{core}} =$ 1.11 W which corresponds to 2.22 % of the output power.

/ 3 pt.

Q28: THERMAL CONSIDERATION

For the worst operating condition, calculate the total losses (copper plus core) expected in your transformer and compare them with the loss budget you defined in Q6. Estimate the temperature rise of the designed transformer. You can find values for the thermal resistance R_{th} and the temperature rise limit of different materials in the TDK EPCOS databook on the pages 161 and 168. Make sure the temperature rise you estimate is allowable for the material. If this is not the case review your core and wire selection.

The total power loss is equal to the sum of core losses and AC and DC resistance wire losses.

$$P_{tot} = P_{core} + P_{Cu,ac} = 1.1124\,[\mathrm{W}] + 0.4251\,[\mathrm{W}] = 1.5375\,[\mathrm{W}]$$

The temperature rise is therefore

$$\Delta T = R_{th}P_{tot} = 22\,[\mathrm{K/W}] \times 1.5375\,[\mathrm{W}] = 33.8\,[\mathrm{K}]$$

This value is less than the maximum allowable temperature rise of $50\,[\mathrm{K}]$.

$P_{tot} =$ 1.53 W $\Delta T =$ 33.82 K

/ 3 pt.

TRANSFORMER DESIGN SUMMARY

Q29: LLC TRANSFORMER DESIGN

Fill Table 5 given below with your design results. Do not forget to include the units.

Table 5 LLC transformer design summary

Electrical specification		
Desired Magnetizing inductance	L_m^*	$6.09\mu H$
Designed Magnetizing inductance	L_m	$9.07\mu H$
Primary current	$I_{L,w1,rms}$	3.28 A
Secondary current	$I_{L,w2,rms}$	1.78 A
Operating frequency range	$f_{sw,min} - f_{sw,max}$	115 kHz
Core specification		
Core shape and size		E32/16/9
Coil former		B66229
Core material		N27 or N28
Max flux density	ΔB	0.35 T
Total Air gap length	l_g	1.30 mm
Number of Kapton tape layers per side		10
Winding specification		
wire 1 diameter	$\varnothing$	1 mm
number of turns for wire 1	N	8
wire 2,1 diameter	$\varnothing$	0.9 mm
number of turns for wire 2,1	N	8
wire 2,2 diameter	$\varnothing$	0.9 mm
number of turns for wire 2,2	N	8
Losses and temperature rise		
Core losses	P_{core}	1.11 W
DC Winding losses	$P_{Cu,dc}$	0.20 W
Total inductor losses	$P_{L,loss}/P_{out}$	3.47 %
Expected Temperature rise	ΔT	33.8 K

/ 1 pt.

Q30: OVERALL EFFICIENCY OF THE LLC CONVERTER

Taking into account the results of the Loss Tool of Report 1, estimate the best-case and the worst-case overall efficiency of your LLC converter for the nominal output power considering the transformer losses estimated theoretically (Q26 and Q27).

The worst case overall efficiency should occur at the minimum voltage input, 40 V:
$P_{d,cond,vmin} = 1.8305\,W$
$P_{sw,cond,vmin} = 0.6848\,W$
$P_{sw,on/off,vmin} = 0.2022\,W$
$P_{Cu,dc,vmin} = 0.1958\,W$
$P_{Cu,ac,vmin} = 0.4251\,W$
$P_{core,vmin} = 1.11\,W$

$$P_{LLC,vmin} = P_{d,cond,vmin} + P_{sw,cond,vmin} + P_{sw,on/off,vmin} + P_{Cu,ac,vmin} + P_{core,vmin} = 4.24\,\mathrm{W}$$

$$\eta_{LLC,vmin} = \frac{P_{out}}{P_{out} + P_{LLC,vmin}} = \frac{50\,[\mathrm{W}]}{50\,[\mathrm{W}] + 4.24\,[\mathrm{W}]} \times 100\,\% = 92.1\,\%$$

The best case overall efficiency should occur at the maximum voltage input, 50 V:

$P_{d,cond,vmax} = 1.5714\,\mathrm{W}$
$P_{sw,cond,vmax} = 0.4547\,\mathrm{W}$
$P_{sw,on/off,vmax} = 0.3663\,\mathrm{W}$
$P_{Cu,dc,vmax} = 0.1603\,\mathrm{W}$
$P_{Cu,ac,vmax} = 0.3473\,\mathrm{W}$
$P_{core,vmax} = 1.11\,\mathrm{W}$

$$P_{LLC,vmax} = P_{d,cond,vmax} + P_{sw,cond,vmax} + P_{sw,on/off,vmax} + P_{Cu,ac,vmax} + P_{core,vmax} = 3.84\,\mathrm{W}$$

$$\eta_{LLC,vmax} = \frac{P_{out}}{P_{out} + P_{LLC,vmax}} = \frac{50\,[\mathrm{W}]}{50\,[\mathrm{W}] + 3.84\,[\mathrm{W}]} \times 100\,\% = 92.8\,\%$$

$\eta_{\mathrm{LLC},best} =$ 92.1 %

$\eta_{\mathrm{LLC},worst} =$ 91.8 %

/ 3 pt.

TRANSFORMER BUILDING PROCEDURE

Q31: WIRING OF THE TRANSFORMER

Based on the theoretical calculations done above, choose:

- 1x Coil former **!! Careful: Pins are easy to bend and break! The main structure is made of plastic, don't push the clamp to hard it can break**
- 2x Core halves **!! Careful: Very fragile! Do not drop !!**
- 2x Yoke

Proceed with these items to the assembly station where you use the coil former to start wiring your transformer. Wind the appropriate number of turns for your primary and your two secondaries (Q20), using the appropriate wire according to your choices (Q16). It is strongly suggested to interleave the tree winding, especially if your desired resonance (and therefore leakage) inductance is very low ($\leq 2\mu H$), this means wiring all your three windings at the same time. If you can allow a big leakage inductance you can consider wire one winding at a time and try different disposition of primary and secondary. **Note**: leave some margin (ca. 4-6 cm) at the end of each side of the windings to make following steps easier. **Note**: Mark differently the beginning and end of each of your windings to help connecting them appropriately.
Add a picture after the last step of the above mentioned assembly process.

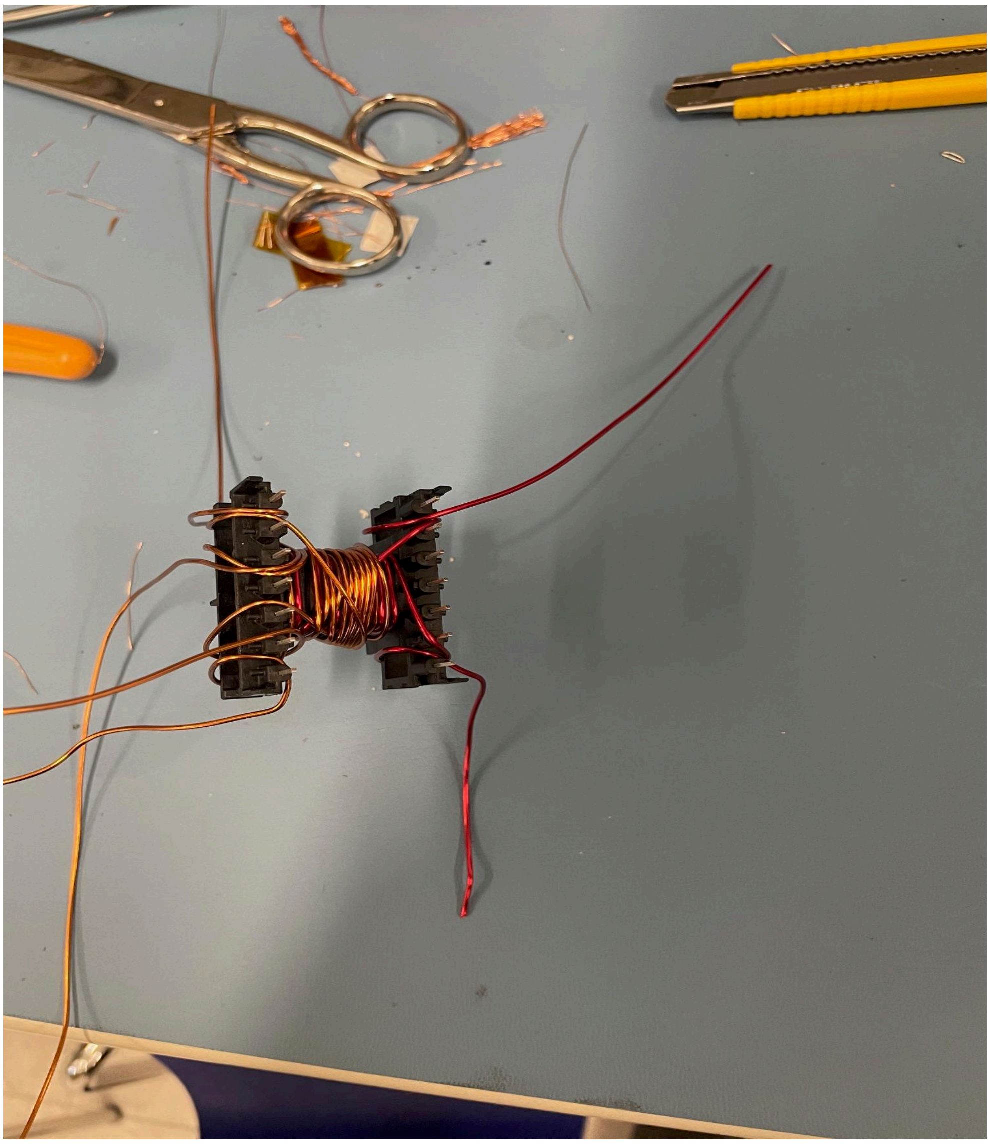


Figure 2 Completed wiring of the transformer.

/ 2 pt.

Q32: AIR GAP AND ASSEMBLY OF THE TRANSFORMER

Following the wiring of your transformer, proceed with:

- Inserting a single core half into the coil former
- Adding the right amount of Kapton tape layers on the two external legs
- Inserting the second core half into the other side of the coil former
- Use the yokes to hold the transformer together

Note: it can require quite a bit of force to install the yokes, use the provided tools and be careful to not break the cores.
Add a picture after the last step of the above mentioned assembly process.

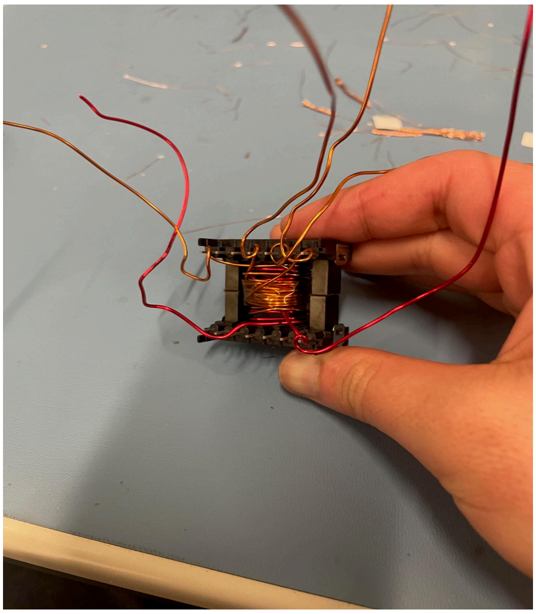


Figure 3 Implementation of air gap into transformer.

After wiring and testing, the number of Kapton layers required add up to 12 per side, giving us a $L_{m,real} = 7.4\mu H$

/ 2 pt.

Q33: VERIFYING THE WIRING DIRECTIONS

Using the RLC meter as a supply connected to the terminals of the primary winding, verify the winding direction of the secondaries winding by following the steps below:

- Set the frequency on the RLC to 10kHz
- Mark the terminal of the primary winding connected to the high potential of the RLC
- Measure the voltage across the secondary windings
- If the voltage is in phase with the primary voltage, mark the positive terminal, otherwise mark the negative terminal

Provide a picture of the inductor with the markings on the three windings.

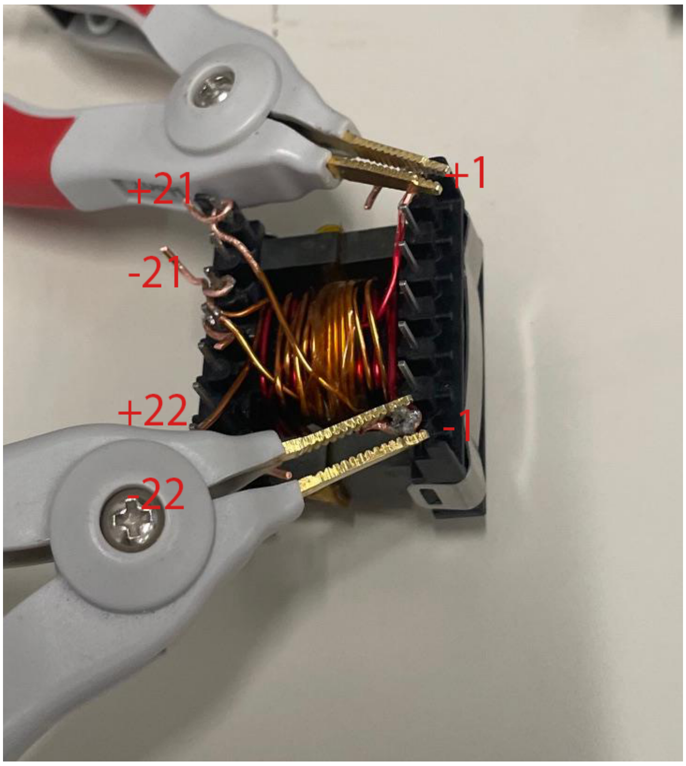
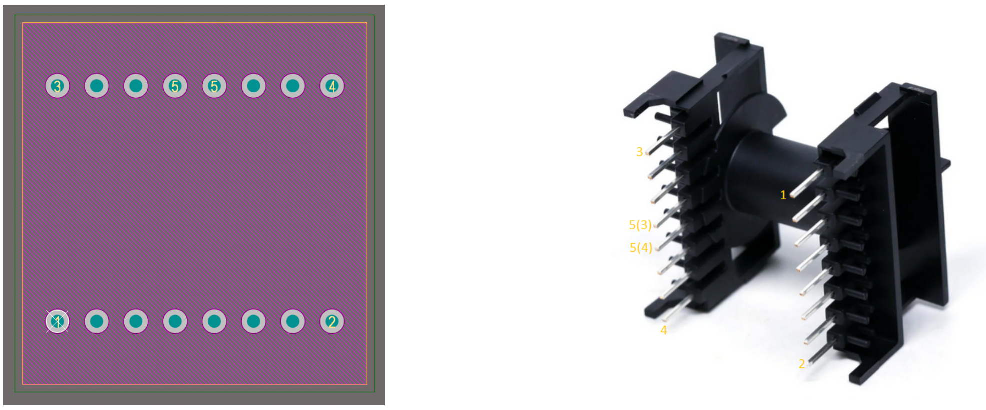


Figure 4 Inductor marked with positive and negative terminals of all three windings.

/ 2 pt.

Q34: SOLDERING

Solder the windings to the respective pins of the coil former and provide a picture of the final soldered transformer. **Note**: Make sure to solder the winding terminals to the right pins **Note**: You need to remove isolation from the wires before soldering. If you are using bare wire you can scratch the varnish with sandpaper or camps' or scissors' blades. If you are using Litz wires you need to terminate them using soldering bath (keep the wire inside the bath for 10-20 seconds according to the size of your wire)
Add a picture after completing the soldering process.



(a) Footprint

(b) Coilformer

Figure 5 Transformer suggested connection: Solder the beginning of your primary to pin 1, the its end to 2; Solder the beginning of your first secondary to pin 3, and its end to pin 5(3); Solder the beginning of your second secondary to pin 5(4), and its termination to pin 4

Figure 6 Transformer with windings soldered to the respective pins of the coil former.

/ 2 pt.

TRANSFORMER MEASURING PROCEDURE

Q35: OPEN CIRCUIT TEST WITH RLC METER

Measure your magnetizing inductance using the RLC Meter. Keep both secondaries winding open and measure the inductance (Ls mode) on the primary winding. Repeat the measurements for your minimum, nominal and maximum frequency. Show a picture of your measurement set up. Compare this value with your desired magnetizing inductance. If the value is not matching review your design and building procedure. If needed, one non invasive first attempt solution could be to modify the number of Kapton layers.

Note that in the picture the secondary signal looks bigger but the vertical divisions for the secondary is half of the primary.

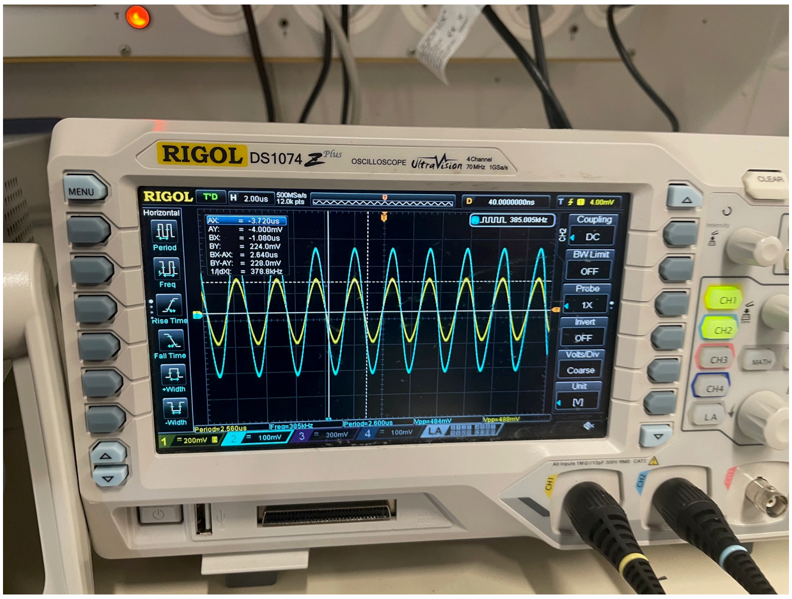


Figure 7 Measurement setup: oscilloscope visualization.

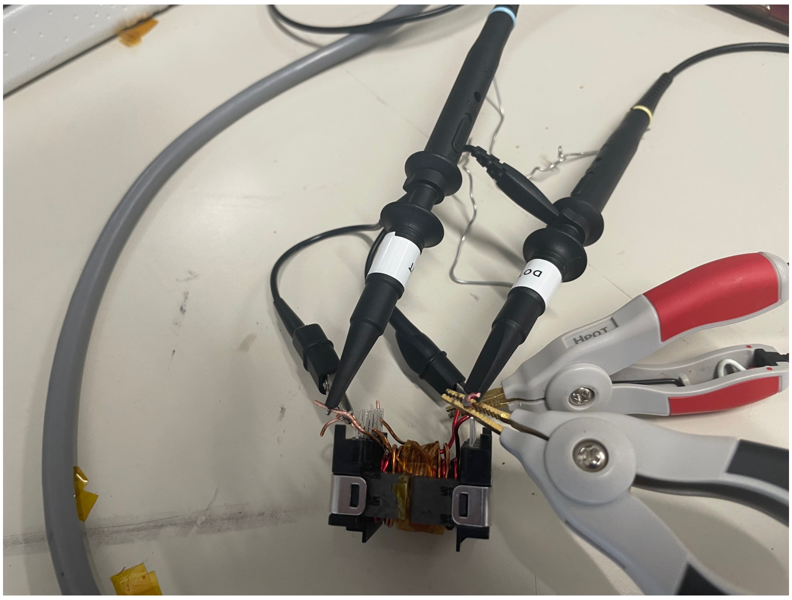


Figure 8 Measurement setup: probe connections to the transformer.

L_m = 7.48 μH	at	f_{min} = 270 kHz	
L_m = 7.47 μH	at	f_{nom} = 310 kHz	
L_m = 7.46 μH	at	f_{max} = 385 kHz	/ 3 pt.

Q36: SHORT CIRCUIT TEST WITH RLC METER

Measure your leakage inductance and resistance using the RLC Meter. Short circuit both secondaries winding using wire or clips, and measure the inductance and resistance (Ls-Rs mode) on the primary winding. Repeat the measurements for your minimum, nominal and maximum frequency. Show a picture of your measurement set up. Compare the inductance value with your desired resonance inductance and make sure that your leakage inductance is smaller than the resonant inductor value that you need. If the constraint is not fulfilled rewind your transformer. Than compare your expected resistance measured with the one you estimated in Q25. **Note**: The value you measure is the series of your primary side resistance plus the parallel of the resistance of your secondary windings reflected to primary side. Notice the effect of frequency on your resistance.

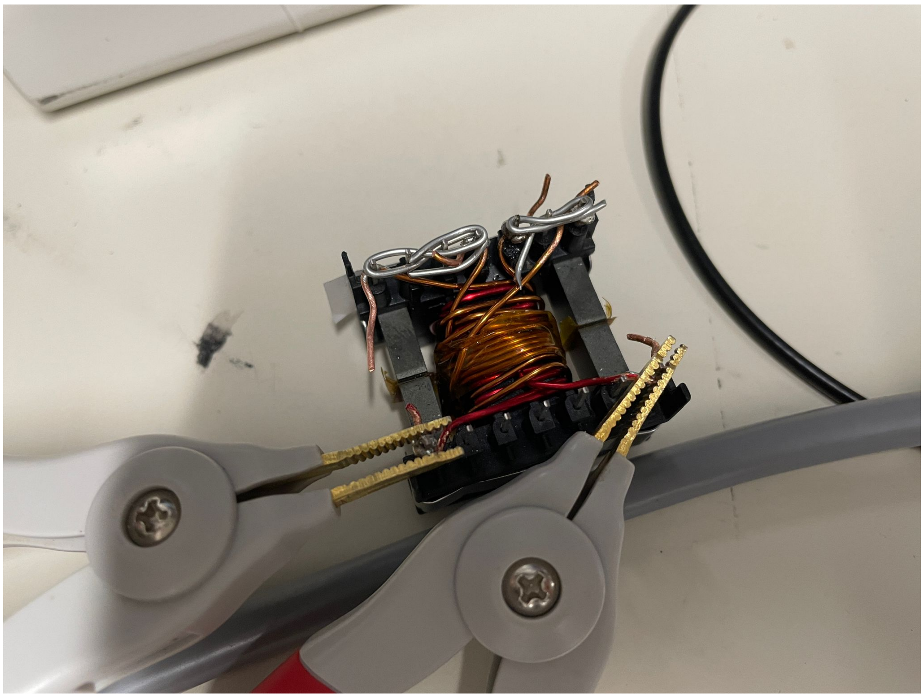


Figure 9 Measurement setup of short circuit test with RLC meter.

The resistance increases as frequency increases. This happens due to the fact that the skin effect also increases as frequency increases.

$L_{leak} = 0.7\ \mu H$	$R_s = 0.16\ \Omega$	at $f_{min} = 270\ kHz$
$L_{leak} = 0.69\ \mu H$	$R_s = 0.17\ \Omega$	at $f_{nom} = 310\ kHz$
$L_{leak} = 0.68\ \mu H$	$R_s = 0.2\ \Omega$	at $f_{max} = 385\ kHz$

/ 4 pt.

Q37: OPEN CIRCUIT TEST WITH BODE 100 METER

Validate the measurements your took in Q35 using the Bode 100 Meter. Keep both secondary windings open and measure the inductance (Impedance Analysis/One-Port/Ls) on the primary winding. Provide a screenshot showing the measured inductance for a frequency range from 100 Hz to 1 MHz.

Measurement: One-Port

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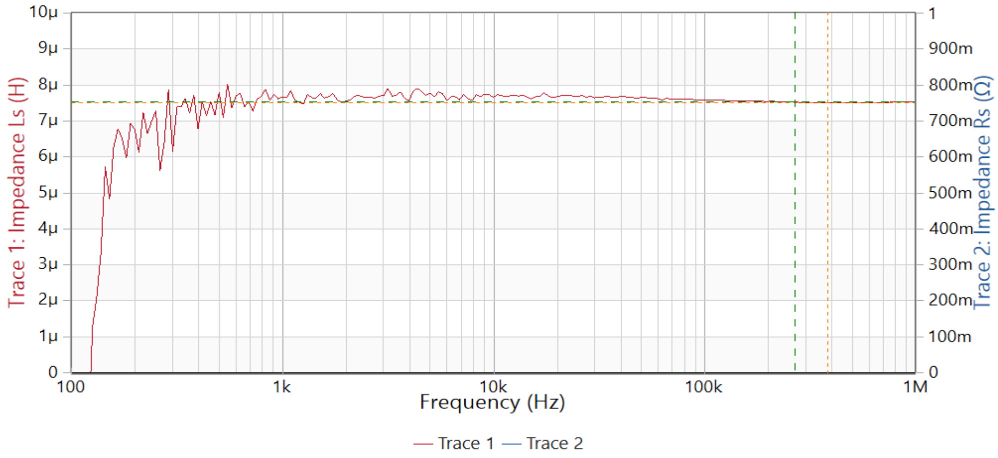

	Cursor 1	Cursor 2	Delta C2-C1
Frequency	270 kHz	385 kHz	115 kHz
Trace 1	**Ls**	**Ls**	**Ls**
Measurement	7,521 µH	7,505 µH	-16,791 nH
Trace 2	**Rs**	**Rs**	**Rs**
Measurement	7,658 Ω	7,041 Ω	-616,464 mΩ

Sweep	
Start frequency:	100 Hz
Stop frequency:	1 MHz
Center frequency:	500,05 kHz
Span:	999,9 kHz
Sweep mode:	Logarithmic
Numer of points:	201

Calibration	Full-Range	User-Range
Impedance	Active	-

Attenuator setting	Channel 1	Channel 2
Reflection	10 dB	10 dB

Hardware setup	
Device type:	Bode100R1
Serial number:	ML700D
Receiver bandwidth:	300 Hz
Output level:	0 dBm
DUT settling time:	0 s

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Figure 10 Measured open circuit inductance and resistance on the primary winding, using the Bode 100 Meter.

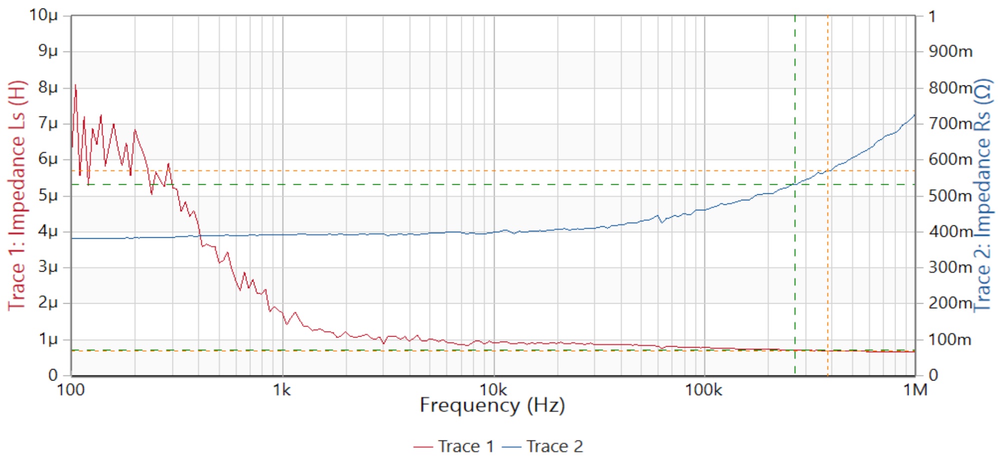
/ 3 pt.

Q38: SHORT CIRCUIT TEST WITH BODE 100 METER

Validate the measurements your took in Q36 using the Bode 100 Meter. Short Circuit both secondaries winding and measure the inductance and resistance (Impedance Analysis/One-Port/Ls+Rs) on the primary winding. Provide a screenshot showing both the measured inductance and the measured resistance for a frequency range from 100 Hz to 1 MHz.

Measurement: One-Port

OMICRON LAB



	Cursor 1	Cursor 2	Delta C2-C1
Frequency	270 kHz	385 kHz	115 kHz
Trace 1	**Ls**	**Ls**	**Ls**
Measurement	711,397 nH	693,245 nH	-18,151 nH
Trace 2	**Rs**	**Rs**	**Rs**
Measurement	532,922 mΩ	569,608 mΩ	36,686 mΩ

Sweep	
Start frequency:	100 Hz
Stop frequency:	1 MHz
Center frequency:	500,05 kHz
Span:	999,9 kHz
Sweep mode:	Logarithmic
Numer of points:	201

Calibration	Full-Range	User-Range
Impedance	Active	-

Attenuator setting	Channel 1	Channel 2
Reflection	10 dB	10 dB

Hardware setup	
Device type:	Bode100R1
Serial number:	ML700D
Receiver bandwidth:	300 Hz
Output level:	0 dBm
DUT settling time:	0 s

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Figure 11 Measured short circuit inductance and resistance on the primary winding, using the Bode 100 Meter.

Q39: SATURATION MEASUREMENTS

Using the power choke meter, execute the saturation test and provide the results below.

- Keep the secondary windings open
- Connect both the Force and Sense cable to the power choke meter and to the terminals of the primary inductance
- Once connected, cover with Plexiglas box and do not touch until the end of the measuring process

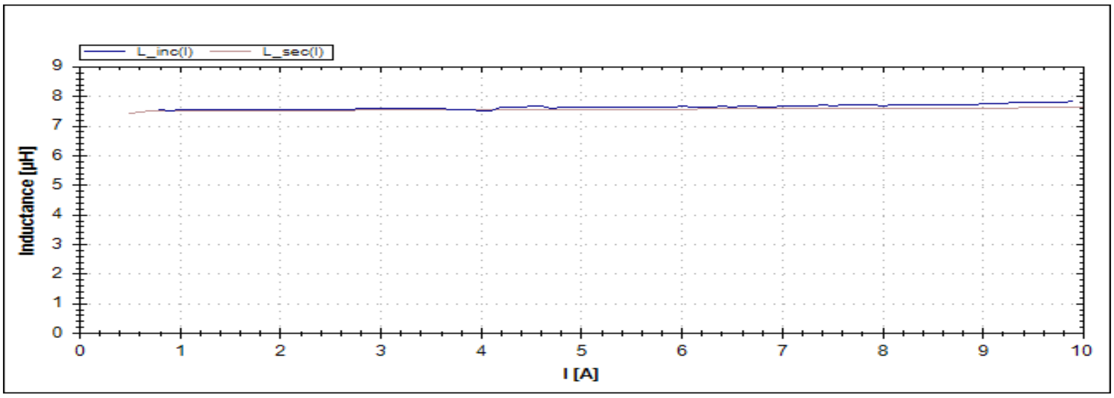
Software settings:

- The max current value corresponds to your maximum input current rounded up
- The measured voltage value corresponds to your maximum input voltage
- For the pulse time enter 10ms

Verify that your core is not saturating and provide the curve of both the incremental and the secant inductance below as well as a picture of the measuring setup.

DPG10 Power Choke Tester

D.U.T.: group20
Inspector:
Date: 11.04.2024 11:01:37
Parameters: 10 A / 15 V / 20 (8) µs
Resistance [Ohm]: 0,0249



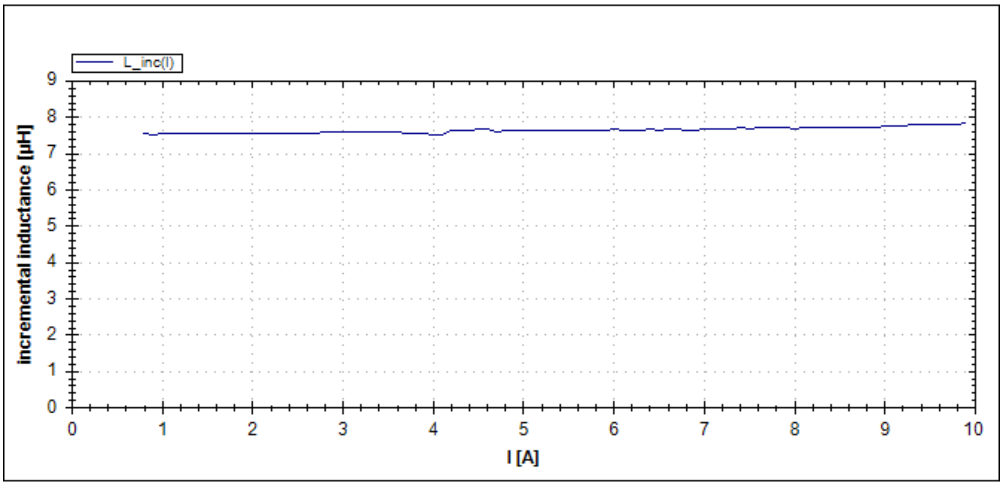
Current [A]	L_{sec} [µH]	Current [A]	L_{sec} [µH]	Current [A]	L_{sec} [µH]	Current [A]	L_{sec} [µH]	Current [A]	L_{sec} [µH]
		2,1	7,51	4,1	7,53	6,1	7,56	8,1	7,58
		2,2	7,51	4,2	7,53	6,2	7,56	8,2	7,58
		2,3	7,51	4,3	7,53	6,3	7,56	8,3	7,59
		2,4	7,51	4,4	7,53	6,4	7,56	8,4	7,59
0,5	7,43	2,5	7,51	4,5	7,54	6,5	7,56	8,5	7,59
0,6	7,47	2,6	7,52	4,6	7,54	6,6	7,57	8,6	7,59
0,7	7,48	2,7	7,52	4,7	7,54	6,7	7,57	8,7	7,59
0,8	7,49	2,8	7,52	4,8	7,54	6,8	7,57	8,8	7,59
0,9	7,49	2,9	7,52	4,9	7,54	6,9	7,57	8,9	7,59
1,0	7,49	3,0	7,52	5,0	7,55	7,0	7,57	9,0	7,60
1,1	7,49	3,1	7,52	5,1	7,55	7,1	7,57	9,1	7,60
1,2	7,50	3,2	7,52	5,2	7,55	7,2	7,57	9,2	7,60
1,3	7,50	3,3	7,53	5,3	7,55	7,3	7,57	9,3	7,60
1,4	7,50	3,4	7,53	5,4	7,55	7,4	7,57	9,4	7,60
1,5	7,50	3,5	7,53	5,5	7,55	7,5	7,58	9,5	7,60
1,6	7,50	3,6	7,53	5,6	7,55	7,6	7,58	9,6	7,61
1,7	7,50	3,7	7,53	5,7	7,55	7,7	7,58	9,7	7,61
1,8	7,51	3,8	7,53	5,8	7,55	7,8	7,58	9,8	7,61
1,9	7,51	3,9	7,53	5,9	7,56	7,9	7,58	9,9	7,61
2,0	7,51	4,0	7,53	6,0	7,56	8,0	7,58	10,0	7,61

Remarks:

Figure 12 Incremental and secant inductance results.

DPG10 Power Choke Tester

D.U.T.:	group20
Inspector:	
Date:	11.04.2024 11:01:37
Parameters:	10 A / 15 V / 20 (8) µs
Resistance [Ohm]:	0,0249



Current [A]	L_{inc} [µH]	Current [A]	L_{inc} [µH]	Current [A]	L_{inc} [µH]	Current [A]	L_{inc} [µH]	Current [A]	L_{inc} [µH]
		2,1	7,54	4,1	7,50	6,1	7,64	8,1	7,69
		2,2	7,54	4,2	7,61	6,2	7,62	8,2	7,70
		2,3	7,54	4,3	7,62	6,3	7,64	8,3	7,69
		2,4	7,53	4,4	7,63	6,4	7,64	8,4	7,71
		2,5	7,55	4,5	7,65	6,5	7,64	8,5	7,71
		2,6	7,55	4,6	7,67	6,6	7,65	8,6	7,71
		2,7	7,56	4,7	7,59	6,7	7,65	8,7	7,72
0,8	7,54	2,8	7,56	4,8	7,61	6,8	7,64	8,8	7,72
0,9	7,52	2,9	7,58	4,9	7,61	6,9	7,63	8,9	7,72
1,0	7,53	3,0	7,57	5,0	7,61	7,0	7,64	9,0	7,73
1,1	7,52	3,1	7,58	5,1	7,61	7,1	7,65	9,1	7,74
1,2	7,52	3,2	7,58	5,2	7,62	7,2	7,65	9,2	7,74
1,3	7,53	3,3	7,58	5,3	7,62	7,3	7,67	9,3	7,77
1,4	7,53	3,4	7,58	5,4	7,62	7,4	7,69	9,4	7,79
1,5	7,52	3,5	7,59	5,5	7,61	7,5	7,68	9,5	7,77
1,6	7,53	3,6	7,60	5,6	7,62	7,6	7,70	9,6	7,77
1,7	7,54	3,7	7,55	5,7	7,64	7,7	7,69	9,7	7,78
1,8	7,54	3,8	7,54	5,8	7,63	7,8	7,69	9,8	7,80
1,9	7,54	3,9	7,53	5,9	7,63	7,9	7,70	9,9	7,82
2,0	7,54	4,0	7,51	6,0	7,65	8,0	7,67		

Remarks:

Figure 13 Incremental inductance results.

We can see that the core doesn't saturate even at a current of 10A which is more than twice our peak current. After another test, the core begins to saturate at around 23A.

/ 4 pt.

Q40: MAGNETIZING CURRENT AND VOLTAGE RATIO CHECK

Using the provided hardware setup excite your transformer to your maximum and minimum frequency.

- Use DC power supply to provide auxiliary power to the Half Bridge (5V)
- Use DC power supply to input power to the Half Bridge (45V)
- Use Tektronix function generator to provide the switching signal to the half bridge (square-wave with amplitude 5Vpp)
- Connect your the output of the Half Bridge to the primary of your transformer

For your minimum and maximum frequencies report the oscilloscope acquisition of primary voltage, secondary voltages and magnetizing current.

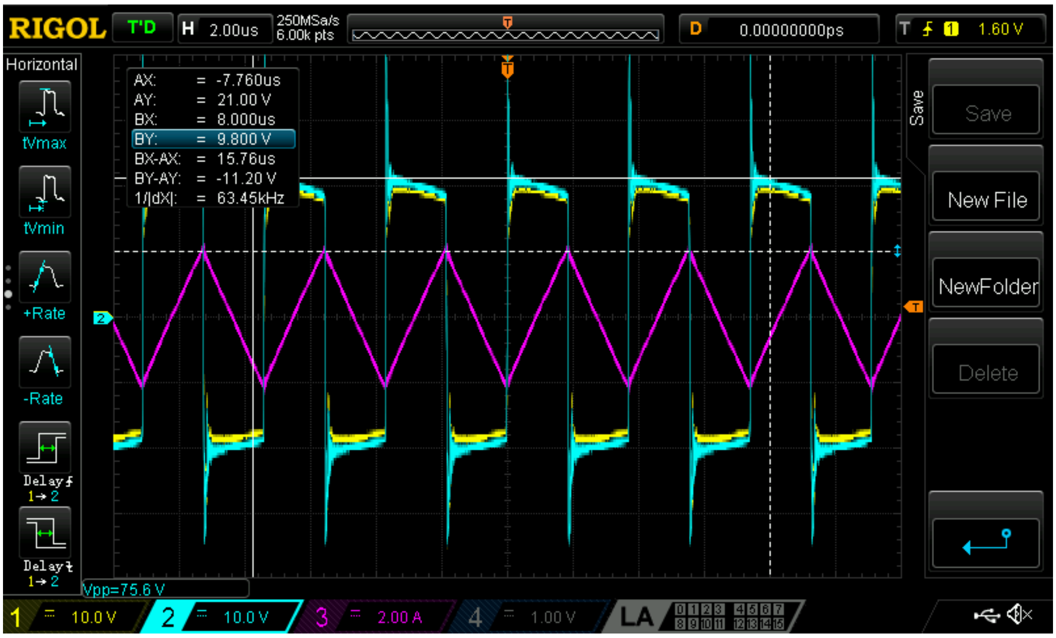


Figure 14 Oscilloscope acquisition of primary voltage, secondary voltages, and magnetizing current at the minimum frequency of 270 kHz and the minimum input voltage of 40 V.

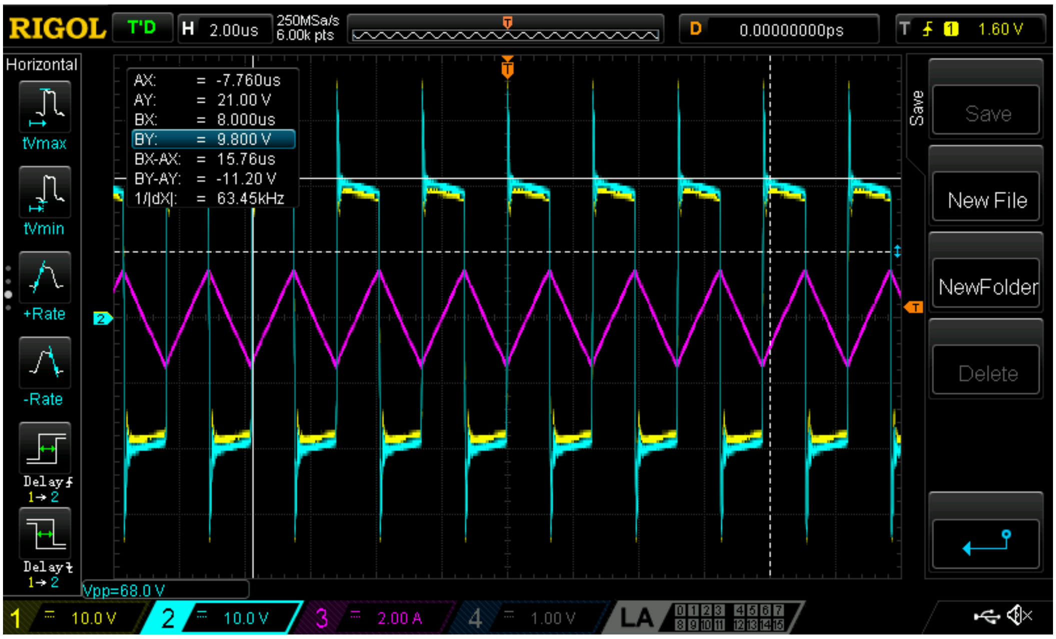


Figure 15 Oscilloscope acquisition of primary voltage, secondary voltages, and magnetizing current at the resonant frequency of 385 kHz and the minimum input voltage of 40 V.

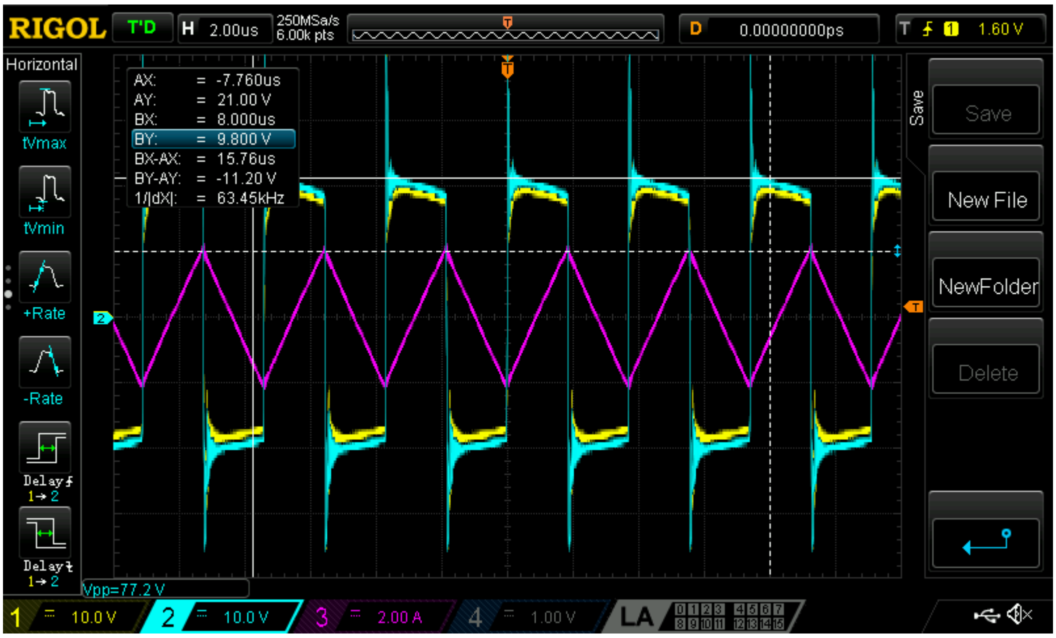


Figure 16 Oscilloscope acquisition of primary voltage, secondary voltages, and magnetizing current at the minimum frequency of 270 kHz and the maximum input voltage of 50 V.

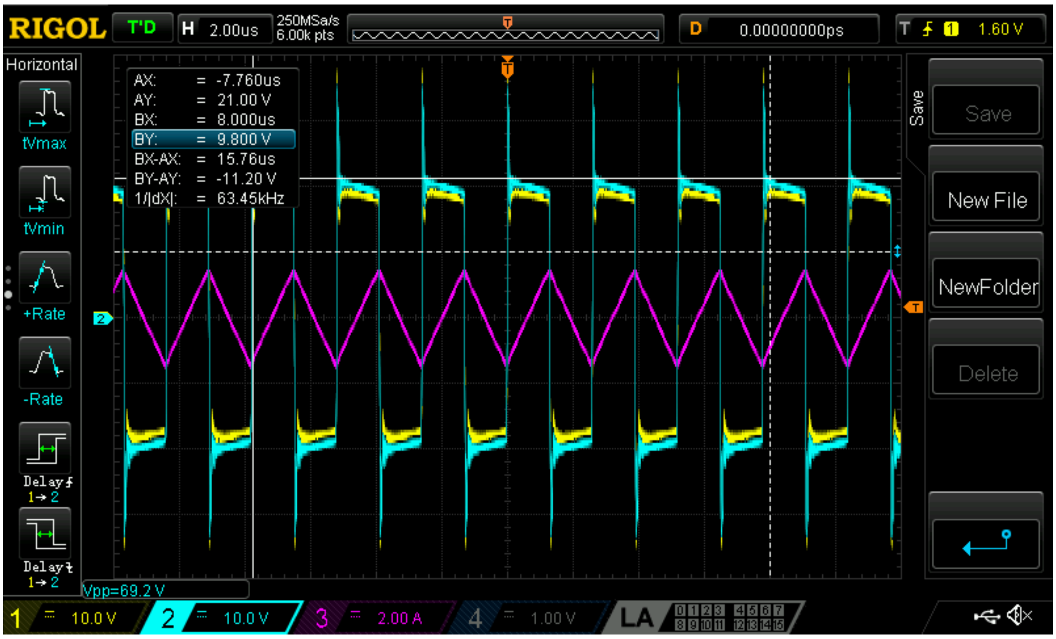


Figure 17 Oscilloscope acquisition of primary voltage, secondary voltages, and magnetizing current at the resonant frequency of 385 kHz and the maximum input voltage of 50 V.

The transformer works correctly, but it has an voltage peak at the start of each rising edge.

/ 4 pt.

Q41: HEAT-RUN TEST

Using the set up provided for previous question, execute a heat-run test. Provide a picture of the test-setup as well as two thermal images, one done prior to the test and one after 15 minutes of test.

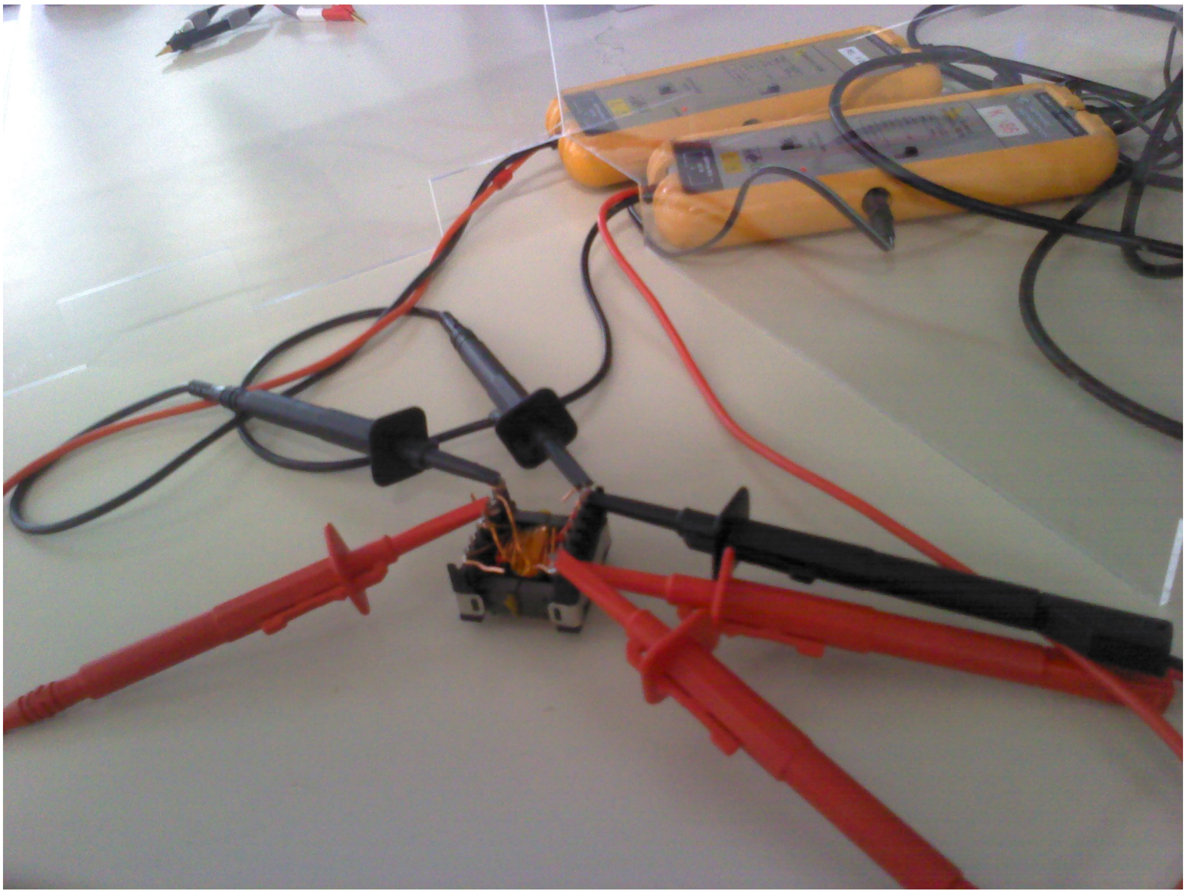


Figure 18 Test setup prior to heat test.

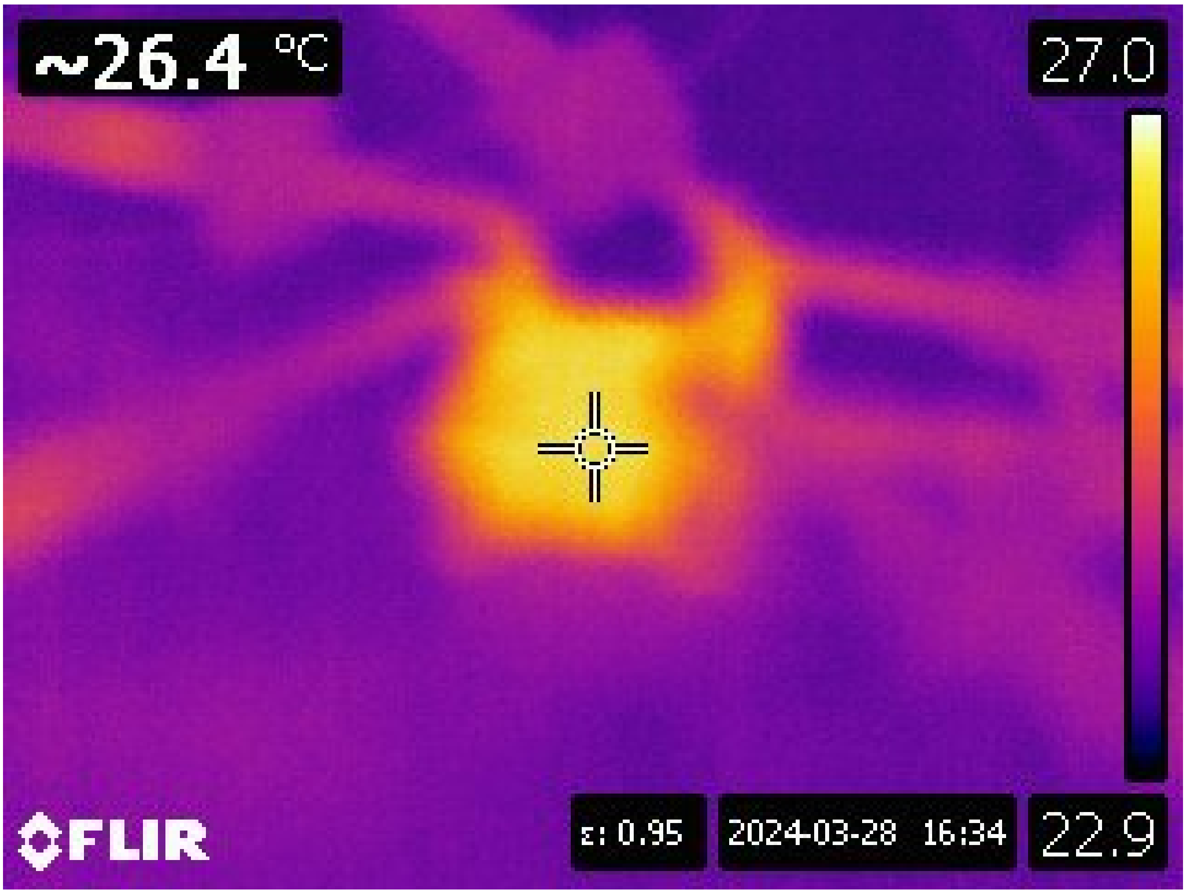


Figure 19 Thermal image of transformer prior to heat test.

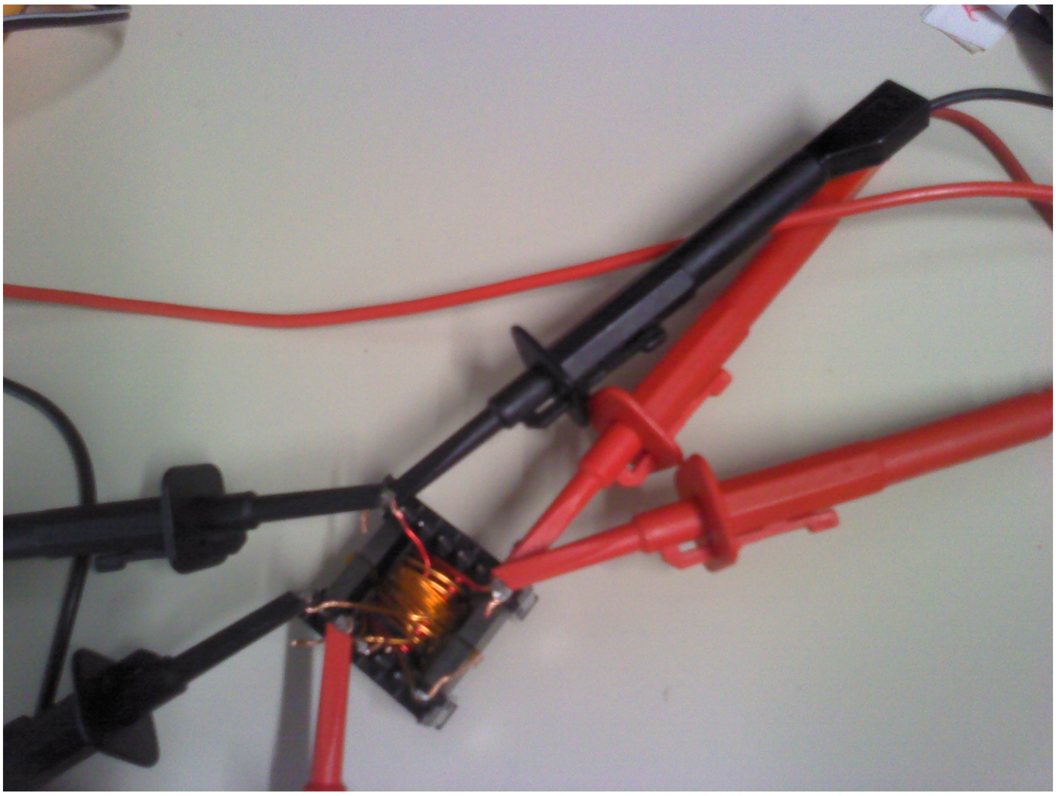


Figure 20 Test setup after completion of heat test.

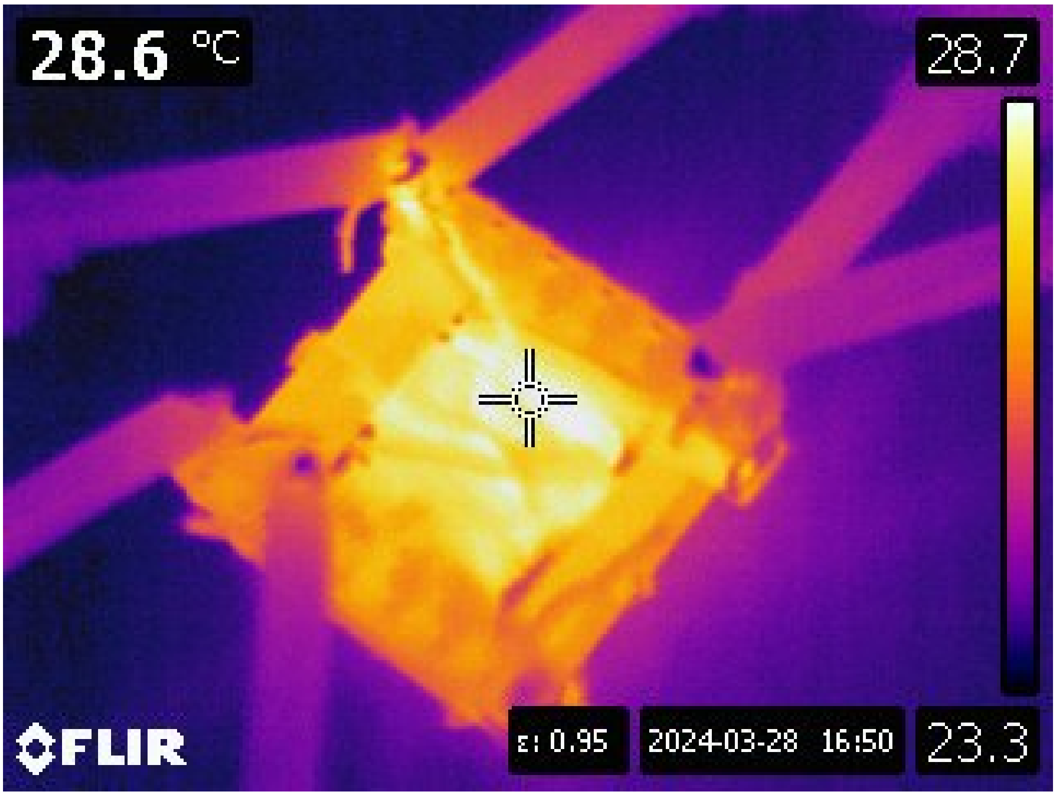


Figure 21 Thermal image of transformer after completion of heat test.

After 15 minutes the temperature rise is minimal at around 2.2$^{\circ}C$

T_{init} = 26.4 $^{\circ}C$	T_{final} = 28.6 $^{\circ}C$	/ 3 pt.

DESIGN OF THE RESONANT INDUCTOR

The aim of this last section is to design and build your external inductor to integrate your leakage inductance and reach the desired value for your resonant inductance. This process is also iterative, please be aware that your could need to reconsider your choices. Questions of this section represent and independent iterative loop with respect to the previous (it is only influenced by the measured leakage inductance Q36 and Q38). Your inductor will be built winding one wire (choose the same wire you used for the primary side of your transformer) around one toroidal core. Be aware that it may not be possible to realize exactly the value of your choice, small deviation can be excepted, they may be compensated when choosing your resonant capacitor in Report 3 or simply tolerated.

Q42: EVALUATE THE EXTERNAL INDUCTANCE

Based on the measured leakage inductance (Q36 validate in Q38), and on the desired L_r, calculate the external inductance you need to add in order to reach the desired inductance value.

From question Q36 we obtained that the measured L_r is in between $0.7\mu H$ and $0.68\mu H$. The desired L_r is $1.52\mu H$. As the the inductors are in series:

The minimum external inductance required is $L_{ext,min} = L_r - L_{r,measured} = 1.52[\mu H] - 0.7[\mu H] = 0.82[\mu H]$.

The maximum external inductance required is $L_{ext,max} = L_r - L_{r,measured} = 1.52[\mu H] - 0.68[\mu H] = 0.84[\mu H]$.

Therefore, the external inductance value should be between $[0.82, 0.84]\mu H$.

$L_{\text{added}} = 0.83$ μH | / 2 pt.

Q43: DESIGN OF THE EXTERNAL INDUCTANCE

Choose one of the core in the Table 6. Evaluate the integer number of turns needed to reach your a value L_s as close as possible to the desired L_{added}

Using the same formula as the transformer we obtain:

$$N = \sqrt{\frac{L_{added}}{A_L}}$$

The selected core is core B with Litz wire and $N = 6$. The change of wire type comes from Q46 where the losses from a magnetizing wire paired with core A are too high. (For the magnetizing wire core B cannot be selected because the value of B is also high). Substituting $N = 6$ into the formula above we obtain: $L_s = N^2 A_L = 6^2 \times 0.24 \times 10^{-7}[H/N^2] = 0.86\mu H$. Additionally, because with 6 turns the B value for the inductor is still too high we have decided to add another core in parallel.

Selected core = 5967001801 | $N_{L,s} = 6$ | $L_s = 0.86$ μH | / 4 pt.

Table 6 Available toroids

Ref.	Part Number	Material	$A_L[nH/N^2]$	μ_r	Link
A	5968001801	68	7.3	16	Fair-rite 68
B	5967001801	67	24	40	Fair-rite 67

Q44: CHECK FOR B VALUE OF YOUR INDUCTOR

Evaluate the magnetic flux value in your inductor considering your pick primary current and the number of turn you selected in Q43. To limit the losses do not allow it to be higher than 30mT. If you can not fulfill this requirement, try to use the other available core. If this solution is not enough you can parallel two cores, this will have the effect of doubling the core area and therefore halve the inductance value for the same number of turns. Go back to previous question and recalculate the number of turns. Indicate "2x" in your selected core if you need to use two cores in parallel.

From inductance of a toroidal core the formula for B with two cores in parallel is:

$$B = \frac{Ls \times I_{peak}}{n \times A_c} = \frac{0.864[\mu H] \times 4.76[A] \times 10^4}{6 \times 0.260[cm^2]} = 26.4[mT]$$

$B_{Ls,peak}$ = 26.4 mT

/ 3 pt.

Q45: WINDING AND MEASUREMENT OF THE INDUCTOR

Using the same wire you selected for your primary transformer wind the calculated number of turns on the selected core. Terminate your wires using the same procedure as for your transformer. Using the RLC meter evaluate Ls and Rs at your minimum and maximum frequency. **Note**: the toroidal cores are also very fragile, manage with caution! **Note**: Distribute your turns evenly around the core to obtain a more similar result to the one calculated theoretically. You can also adjust the position of your turns to tailor your inductor value to the desired one. Once you have fixed the optimal position fix the two winding endings to the core with a small amount of glue or tape (e.g. use the glue gun). Show a picture of your inductor.

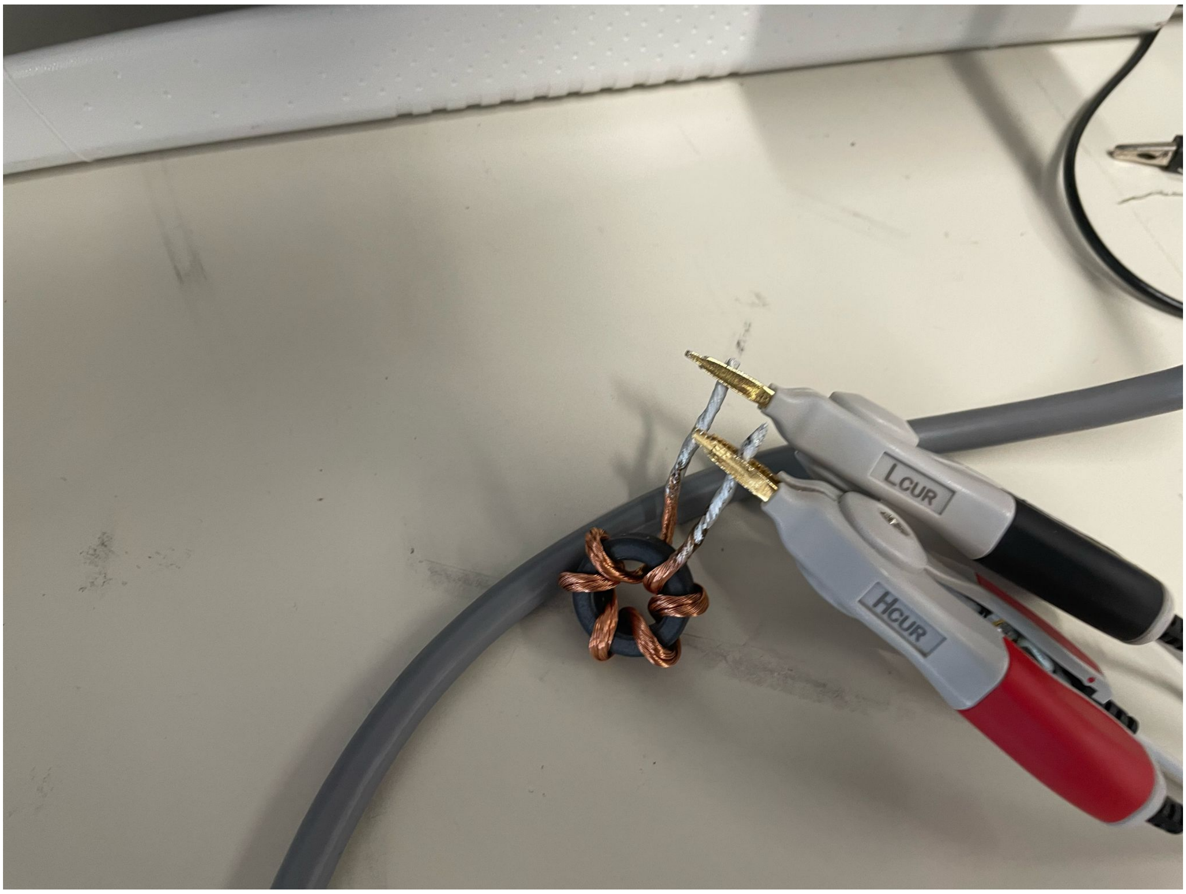


Figure 22 Inductor with finalized winding position.

L_s = 0.9 μH	and	R_s = 0.012 Ω	at	f_{min}= 270 kHz		
L_s = 0.94 μH	and	R_s = 0.011 Ω	at	f_{max}= 385 kHz		/ 5 pt.

Q46: CHECK EXPECTED COPPER LOSSES IN THE INDUCTOR

Take into account your primary side RMS current and the R_s you measured in Q45 for your maximum frequency. Evaluate the copper losses expected in your inductor and calculate the percentage of the nominal output power to which these losses correspond to. **Note**: It would be advisable not to allow more than 0.5W copper losses in order to avoid heating problems. It this happens it is suggested to change the wire to reduce the resistance (you are eventually allowed to parallel two wires).

The copper losses expected in our inductor are calculated as follows.

$$P_{Cu,L,Vmin} = I^2_{lr,rms,min}R_{s,min} = 3.28\,[\mathrm{A}]^2 \times 0.012[\Omega] = 0.129[W]$$

This corresponds to 0.26 % of the output power.

$$P_{Cu,L,Vmax} = I^2_{lr,rms,max}R_{s,max} = 2.90\,[\mathrm{A}]^2 \times 0.011[\Omega] = 0.096[W]$$

This corresponds to 0.19 % of the output power.

The maximum copper losses therefore occur at an input of Vmin.

$P_{cu,L}$ = 0.129 W which corresponds to 0.26 % of output power / 2 pt.