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Title

R2: BOOST CONVERTER – INDUCTOR DESIGN

Course Name

EE-365 Power Electronics

Keywords

Boost Converter, Inductor Design, Capacitor Selection

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INDUCTOR SPECIFICATIONS AND DESIGN CONSTRAINTS

The second part of the project deals with the design and realization of the Boost 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 parts of the project. For currents, select the highest values that may occur during the operation of your converter. Since the operating frequencies of the Boost converters designed in the project can vary from 100 kHz to 500 kHz, ferrite was chosen as a core material. Therefore, two particular ferrite materials are considered, N27 and the more advanced N87. While some cores available for this course are also made of the N87 ferrite material, start all your design considerations with the N27 ferrite if available.

To successfully complete the third 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. Navigation through datasheets is required for some of the questions. Please note that notations may vary. Therefore, always look for the parameter rather than the symbol.

Table 1 Given parameters and design requirements for the Boost converter inductor.

Property	Value	Unit
f_{sw}	125	kHz
L_{min}	141	μH
L_{selected}	230	μH
ΔI_{L}	0.7	A
$I_{L,\mathrm{avg}}$	2.38	A
$I_{L,\mathrm{rms}}$	2.38	A
$I_{L,\mathrm{pk}}$	2.46	A
$P_{L,\mathrm{loss,goal}}$	< 2	%
ΔT_{goal}	< 30	K

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 N27 and N87 are given in the ferrite databook. 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, core losses and ripple waveform distortion.

$B_{\mathrm{pk,max}}$ = 350 mT

/ 2 pt.

Q2: ESTIMATION OF THE WINDOW UTILIZATION FACTOR

The core window area is besides by 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. Select a plausible value from experience that you know of. Once the core sample is wound you will be able to improve this estimate for the next inductor design iteration.

K_{u} = 0.6

/ 2 pt.

Q3: RESISTANCE BUDGET FOR THE INDUCTOR

In order to limit the conduction losses during the design phase, calculate the budget for the maximal value of the inductor resistance R_L, so that the ohmic inductor losses are in accordance with the requirement set in Table 1. For simplicity, you can neglect high-frequency effects in this course.

$$
\begin{aligned}
R_{L,max} &= \frac{P_{L,loss,goal}}{I_{L,rms}^2} \\
&= \frac{0.02 \cdot 50\,\mathrm{W}}{5.66\,\mathrm{A}} \\
&= 176\,\mathrm{m\Omega}
\end{aligned} \tag{1}
$$

$R_{L,\mathrm{max}}$ = 176 mΩ

/ 2 pt.

Q4: CURRENT DENSITY CONSTRAINT

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. Therefore, the current density of the magnet wire J_w is typically constrained to 2-5 A/mm^2. It is a trade-off between copper losses, temperature rise and power density. Select a certain current density constraint to start your design. Once the first inductor design is calculated and/or measured, 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 may not be possible to exactly match the selected value.

J_w = 3.5 A mm^{-2}

/ 2 pt.

PRESELECTION OF INDUCTOR CORES

Magnetic core manufacturers provide a vast variety of core shapes and sizes. Their databooks provide charts and tables that allow you to narrow down your core selection according to a typical power handling capability under given circumstances. In this course, a preselection of cores that could handle 50 W of the designed Boost converters has been made and they are listed in Table 2.

Table 2 Available core materials and core shapes.

Core shape	Ungapped N27 core	Ungapped N87 core	Coil former	Yoke
E20/10/6	B66311G0000X127	B66311G0000X187	B66206B1110T001	B66206A2010X000
E25/13/7	B66317G0000X127	B66317G0000X187	B66208X1010T001	B66208A2010X000
541 ETD29/16/10	B66358G0000X127	-	B66359X1014T001	B66359S2000X000
E30/15/7	-	B66319G0000X187	B66232B1114T001	B66232A2010X000
E32/16/9	-	B66229G0000X187	B66230A1114T001	B66362A2000X000
ETD34/17/11	B66361G0000X127	-	B66362X1014T001	B66362A2000X000
ETD39/20/13	B66363G0000X127	-	B66364B1016T001	B66364A2000X000
ETD44/22/15	B66365G0000X127	-	B66366B1018T001	B66366A2000X000

Q5: ENERGY HANDLING CAPABILITY OF THE INDUCTOR

Contrary to transformers, inductors store energy. In case of gapped cores, the energy is stored in the air gap. The I^2L charts in the databooks (see FXC_HB2013 pag. 32 and 35) show the required air gap length to store that energy for each core shape. Calculate the required I^2L value for your selected inductance value and your peak current.

$$
\begin{aligned}
I^2L &= L \cdot \left(I_{L,peak}\right)^2 \\
&\approx 0.000\,23\,\mathrm{H} \cdot (2.462\,81\,\mathrm{A})^2 \\
&\approx 0.001\,395\,05\,\mathrm{J} \\
I^2L &\approx 1.395\,05\,\mathrm{mJ}
\end{aligned}
\tag{2}
$$

$I^2L =$ 1.4 mJ

/ 3 pt.

Q6: AIR GAP ESTIMATE

With the help of the calculated value for the energy handling capability and an I^2L chart provided in the material databooks, estimate the required air gap length for the available cores and fill the table below. The air gap stretches the effective $B - H$ magnetization curve and allows you in this way to avoid saturation of the core for a given current. For a given number of turns and a certain core shape, the air gap l_g is a degree of freedom to balance inductance and saturation current. As you can see in the core shape descriptions, there are also core halves available with different machined gaps in the center limb. These halves can be combined to achieve a target air gap length. Nevertheless, in this project cores with equal limbs will be used, i.e. ungapped cores and the tuning of the air gap will be performed with inserting a certain number of layers of Kapton tape.

Table 3 Preselected core shapes and the necessary air gaps.

Core shape	Approx. value of l_g [mm]
E20/10/6	-
E25/13/7	0.7
ETD29/16/10	0.55
E30/15/7	0.3
E32/16/9	0.35
ETD34/17/11	0.4
ETD39/20/13	0.25
ETD44/22/15	0.15

/ 3 pt.

CORE SELECTION WITH THE HELP OF THE AREA PRODUCT

Q7: MINIMAL AREA PRODUCT

Calculate the minimal required area product value $A_{p,min}$ in order to further narrow down the list of inductor cores. The idea is to select a core shape to start your design with, which has small mechanical dimensions, but is large enough to handle the power both electrically and magnetically. Use your Boost inductor specifications and constraints from the beginning of this report. Convert the obtained result of the area product to cm^4.

$$
\begin{aligned}
A_{p,min} &= \frac{L \cdot I_{L,rms} \cdot I_{L,peak}}{B_{pk,max} \cdot J_w \cdot K_u} \\
&\approx \frac{0.000\,23\,\mathrm{H} \cdot 2.379\,63\,\mathrm{A} \cdot 2.462\,81\,\mathrm{A}}{0.35\,\mathrm{T} \cdot 3.5 \times 10^6\,\mathrm{Am}^{-2} \cdot 0.6} \\
&\approx 1.833\,92 \times 10^{-9}\,\mathrm{m}^4 \\
A_{p,min} &\approx 0.183\,392\,\mathrm{cm}^4
\end{aligned}
\tag{3}
$$

$A_{p,min}$ = 0.2 cm^4

/ 4 pt.

Q8: AREA PRODUCT OF THE PRESELECTED CORES

Calculate the required A_p value for all the preselected cores (e.g. see TDK EPXOS databook p. 422 and 423). Eventually, choose the core with the sufficient A_p value and continue designing your inductor with the selected core.

Table 4 Area product of the preselected cores.

Core shape	$A_{c,min}$ [mm^2]	$W_{A,eff}$ [mm^2]	A_p [cm^4]
E20/10/6	31.9	26.65 (g = 0.5)	0.09
E25/13/7	51.5	38.5 (g = 1)	0.198
ETD29/16/10	71	59.17 (g = 1)	0.42
E30/15/7	49	57.564 (g = 0.34)	0.28
E32/16/9	81.4	67.32 (g = 1)	0.55
ETD34/17/11	91.6	78.3 (g = 1)	0.72
ETD39/20/13	123	108.9 (g = 1)	1.34
ETD44/22/15	172	126.29 (g = 1.5)	2.17

Chosen core shape: ETD29/16/10

/ 6 pt.

MAGNET WIRE SELECTION

Q9: BARE WIRE AREA

From the effective inductor current $I_{L,rms}$ and the maximal allowed wire current density J_w, calculate the required bare wire area $A_{w,bare}$. For simplicity, you can neglect high-frequency effects in this course.

$$\begin{aligned} A_{w,bare} &= \frac{I_{L,rms}}{J_w} \\ &\approx \frac{2.379\,63\,\mathrm{A}}{3.5\,\mathrm{A/mm^2}} \\ &\approx 0.679\,894\,\mathrm{mm^2} \end{aligned} \tag{4}$$

$A_{w,bare}$ = 0.68 mm^2

/ 2 pt.

Q10: WIRE SELECTION

From Table 5, select a magnet wire (American wire gauge - AWG - please mind that these values only roughly correspond to the actual wire diameters) that has a conductor area within ± 10 % range of the required $A_{w,bare}$. In case that it is not possible, select a wire with the next smaller cross-section. In the following, calculate the resulting current density $J_{\mathrm{w,result}}$ for the cross-section area $A_{\mathrm{w,selected}}$ of the selected wire.

Table 5 Available magnet wires.

AWG	19	18	16	15	14	13	12
Conductor diameter	0.9 mm	1.0 mm	1.2 mm	1.4 mm	1.6 mm	1.8 mm	2.0 mm

$$
\begin{aligned}
d_w &= 2 \cdot \sqrt{\frac{A_{w,bare}}{\pi}} \\
&\approx 2 \cdot \sqrt{\frac{0.679\,894\,\mathrm{mm}^2}{3.141\,59}} \\
&\approx 0.930\,413\,\mathrm{mm} \\
A_{w,selected} &= \frac{d_{w,sel}}{2}^2 \cdot \pi \\
&\approx \frac{0.9\,\mathrm{mm}}{2}^2 \cdot 3.141\,59 \\
&\approx 0.636\,173\,\mathrm{mm}^2 \\
J_{w,result} &= \frac{I_{L,rms}}{A_{w,selected}} \\
&\approx \frac{2.379\,63\,\mathrm{A}}{0.636\,173\,\mathrm{mm}^2} \\
&\approx 3.740\,54\,\mathrm{A\,mm}^{-2}
\end{aligned} \tag{5}
$$

Selected AWG: 19 | $A_{\mathrm{w,selected}} =$ 0.63 mm^2 | $J_{\mathrm{w,result}} =$ 3.75 A/mm^2 | / 3 pt.

Q11: RELATIVE RESISTANCE OF THE SELECTED WIRE

For the selected copper wire, calculate the relative resistance per unit of length at the temperature of 100 °C. Together with the mean length per turn (MLT) of the coil former, this value will be used to estimate the resistance of the wound inductor once the number of turns is determined.

$$
\begin{aligned}
\frac{R}{l} &= \frac{rho_{cu}}{A_{w,selected}} \\
&\approx \frac{1.678 \times 10^{-8}\ \text{obotoCondensed-Light(2)}\Omega\mathrm{m}}{6.361\,73 \times 10^{-7}\,\mathrm{m}^2} \\
&\approx 0.026\,376\,5\,\Omega\,\mathrm{m}^{-1} \\
\frac{R}{l} &\approx 0.000\,263\,765\,\Omega\,\mathrm{cm}^{-1}
\end{aligned} \tag{6}
$$

$\frac{R}{l} =$ 2.47×10^{-8} Ω/cm | / 3 pt.

CALCULATION OF THE NUMBER OF TURNS AND AIR GAP LENGTH

Q12: NUMBER OF TURNS

For the selected wire, calculate the maximal possible number of turns N_{max} that would fit into the window area of the core. Use the assumed fill factor K_u and the effective window area $W_{A,eff}$ of the coil former. Eventually, select a discrete number of turns.

$$\begin{aligned}
N_{max} &= W_{a,eff,sel} \cdot K_u \cdot J_w \\
&\approx 5.917 \times 10^{-5}\,\mathrm{m}^2 \cdot 0.6 \cdot 3.5 \times 10^{6}\,\mathrm{Am}^{-2} \\
&\approx 124.257 \\
N_{needed} &= \frac{L \cdot I_{L,peak}}{B_{pk,max} \cdot A_{c,min,sel}} \\
&\approx \frac{0.000\,23\,\mathrm{H} \cdot 2.462\,81\,\mathrm{A}}{0.35\,\mathrm{T} \cdot 7.1 \times 10^{-5}\,\mathrm{m}^2} \\
&\approx 22.7946
\end{aligned} \tag{7}$$

N_{max} = 124	$N_{selected}$ = 22	/ 4 pt.

Q13: REQUIRED AIR GAP LENGTH

Determine the needed length of the air gap for your inductor. Use the effective cross-section area of the core and the corresponding magnetic path length (MPL) from the databook (e.g. see TDK EPCOS databook p. 422). Compare the calculated air gap to the initial estimate during core selection from Q6. In order to realize the calculated air gap, Kapton tape layers are inserted between the core halves. The thickness of the tape is given in Table 6. Calculate the actual air gap length imposed by the use of Kapton tape layers (only descrete values are possible). Use this value of the air gap length in the next steps, when required.

Table 6 Available tapes for air gap adjustment.

Film material	Film thickness
Kapton	65 μm

$$\begin{aligned}
l_g &= \frac{N_{selected}^2}{L} \cdot \mu_0 \cdot A_{c,min,sel} \\
&\approx \frac{22^2}{0.000\,23\,\mathrm{H}} \cdot 1.256\,64 \times 10^{-6}\,\mathrm{Hm}^{-1} \cdot 7.1 \times 10^{-5}\,\mathrm{m}^2 \\
&\approx 0.000\,187\,753\,\mathrm{m} \\
l_g &\approx 187.753\,\mu\mathrm{m} \\
N_{layers} &= \frac{l_g}{3 \cdot t_{film}} \\
&\approx \frac{187.753\,\mu\mathrm{m}}{3 \cdot 65\,\mu\mathrm{m}} \\
&\approx 0.962\,833 \\
N_{layers,actual} &= \lceil N_{layers} \rceil \\
&= \lceil 0.962\,833 \rceil \\
&= 1 \\
l_{g,actual} &= N_{layers,actual} \cdot 3 \cdot t_{film} \\
&= 1 \cdot 3 \cdot 65\,\mu\mathrm{m} \\
&= 195\,\mu\mathrm{m}
\end{aligned} \tag{8}$$

l_g = 188 µm	$l_{g,actual}$ = 195 µm	/ 6 pt.

Q14: FRINGING FLUX FACTOR

Calculate the fringing flux factor F_{fringe}, needed to readjust the inductance value, due to fringing flux around the air gap. Use the winding width value G from the coil former data sheet (e.g. FXC_HB2013 pag. 235).

$$G \approx 19.4\,\text{mm}$$

$$\begin{aligned} F_{fringe} &= 1 + \frac{l_{g,actual}}{\sqrt{A_{c,min,sel}}} \cdot \ln \frac{2 \cdot G}{l_{g,actual}} \\ &\approx 1 + \frac{0.000\,195\,\text{m}}{\sqrt{7.1 \times 10^{-5}\,\text{m}^2}} \cdot \ln \frac{2 \cdot 0.0194\,\text{m}}{0.000\,195\,\text{m}} \\ &\approx 1.1225 \end{aligned} \tag{9}$$

G = 19.4 mm	F_{fringe} = 1.12	/ 6 pt.

Q15: ADJUSTMENT OF THE NUMBER OF TURNS DUE TO INDUCTANCE INCREASE

In order to avoid premature core saturation due to increased inductance value, the number of turns needs to be recalculated. Solve the equation that gives the length of the air gap l_g from Q13 for N as a function of L and calculate N_{new}. Consider that with the new number of turns the inductance L has to be reduced by the factor F_{fringe}. Select an integer number of turns.

$$\begin{aligned} N_{selected,new} &= \sqrt{\frac{\frac{L}{F_{fringe}} \cdot l_{g,actual}}{A_{c,min,sel} \cdot \mu_0}} \\ &\approx \sqrt{\frac{\frac{0.000\,23\,\text{H}}{1.1225} \cdot 0.000\,195\,\text{m}}{7.1 \times 10^{-5}\,\text{m}^2 \cdot 1.256\,64 \times 10^{-6}\,\text{Hm}^{-1}}} \\ &\approx 21.1619 \end{aligned} \tag{10}$$

$N_{selected}$ = 22	/ 6 pt.

VERIFICATION OF THE DESIGN CONSTRAINTS

Q16: DC WINDING RESISTANCE

Calculate the DC winding resistance R_L of the designed inductor. Use the MLT value found in the coil former datasheet and the resistance per length for a hot copper wire. Make sure that the obtained value is in accordance with the maximal allowed resistance value calculated in Q3.

$$
\begin{aligned}
R_{L,DC} &= MLT \cdot N_{selected} \cdot \frac{R}{l} \\
&\approx 0.0528\,\mathrm{m} \cdot 22 \cdot 0.026\,376\,5\,\Omega\,\mathrm{m}^{-1} \\
&\approx 0.030\,638\,9\,\Omega \\
\leq R_{L,max} &\approx 0.176\,596\,\Omega \\
\\
\Rightarrow R_{L,DC} &\approx 30.6389\,\mathrm{m\Omega}
\end{aligned}
\tag{11}
$$

R_L = 31 mΩ	/ 3 pt.

Q17: DC COPPER LOSSES

Calculate the DC copper losses of the winding $P_{\mathrm{Cu,dc}}$, which arise due to a current flowing through the inductor. For simplicity, you can neglect high-frequency effects in this course. Check whether the losses are within the target loss budget. In case of constraint violation, explain which parameters need to be readjusted and in which direction. Calculate the percentage of the output power that the losses correspond to.

$$
\begin{aligned}
P_{Cu,DC,nom} &= R_{L,DC} \cdot I_{L,rms}^2 \\
&\approx 0.030\,638\,9\,\Omega \cdot 2.379\,63\,\mathrm{A}^2 \\
&\approx 0.173\,497\,\mathrm{W} \\
P_{Cu,DC} &= \frac{P_{Cu,DC,nom}}{P_{out,nom}} \cdot 100 \\
&\approx \frac{0.173\,497\,\mathrm{W}}{50\,\mathrm{W}} \cdot 100 \\
&\approx 0.346\,994\,\% \\
P_{Cu,DC,max} &= R_{L,DC} \cdot I_{L,rms,(vin,min)}^2 \\
&\approx 0.030\,638\,9\,\Omega \cdot 3.172\,87\,\mathrm{A}^2 \\
&\approx 0.308\,445\,\mathrm{W}
\end{aligned}
\tag{12}
$$

$P_{Cu,dc}$ = 0.17 W	which corresponds to	0.35 % of the output power.	/ 3 pt.

Q18: AC AND PEAK FLUX DENSITIES

Calculate the amplitude of the flux density ripple B_{ac} (for simplicity, use the amplitude of the triangular current). This value will be needed for the core loss calculation. Calculate the peak flux density B_{pk}. Check if the obtained value is in accordance with the initial constraint set in Q1. If this is not the case, explain which parameters need to be readjusted and in which direction.

$$
\begin{aligned}
B_{peak} &= \frac{\mu_0 \cdot N_{selected} \cdot I_{L,peak}}{l_{g,actual}} \\
&\approx \frac{1.256\,64 \times 10^{-6}\,\mathrm{Hm}^{-1} \cdot 22 \cdot 2.462\,81\,\mathrm{A}}{0.000\,195\,\mathrm{m}} \\
&\approx 0.349\,164\,\mathrm{T} \\
B_{peak} &\approx 349.164\,\mathrm{mT} \\
\\
\leq B_{pk,max} &\approx 0.35\,\mathrm{T} \\
\\
B_{ac} &= \frac{N_{selected} \cdot \left(I_{L,peak} - I_{L,avg}\right) \cdot 2 \cdot \mu_0}{l_{g,actual}} \\
&\approx \frac{22 \cdot (2.462\,81\,\mathrm{A} - 2.379\,14\,\mathrm{A}) \cdot 2 \cdot 1.256\,64 \times 10^{-6}\,\mathrm{Hm}^{-1}}{0.000\,195\,\mathrm{m}} \\
&\approx 0.023\,724\,5\,\mathrm{T} \\
B_{ac} &\approx 23.7245\,\mathrm{mT}
\end{aligned}
\tag{13}
$$

B_{ac} = 24 mT | B_{pk} = 349 mT | / 6 pt.

Q19: WINDOW UTILIZATION FACTOR

Based on the recently determined values, calculate the current window utilization factor K_u to check if the winding fits in the core window area, before proceeding to the practical winding. Once the inductor is wound you will be able to adjust your initial estimate of K_u made in Q2 for your calculations.

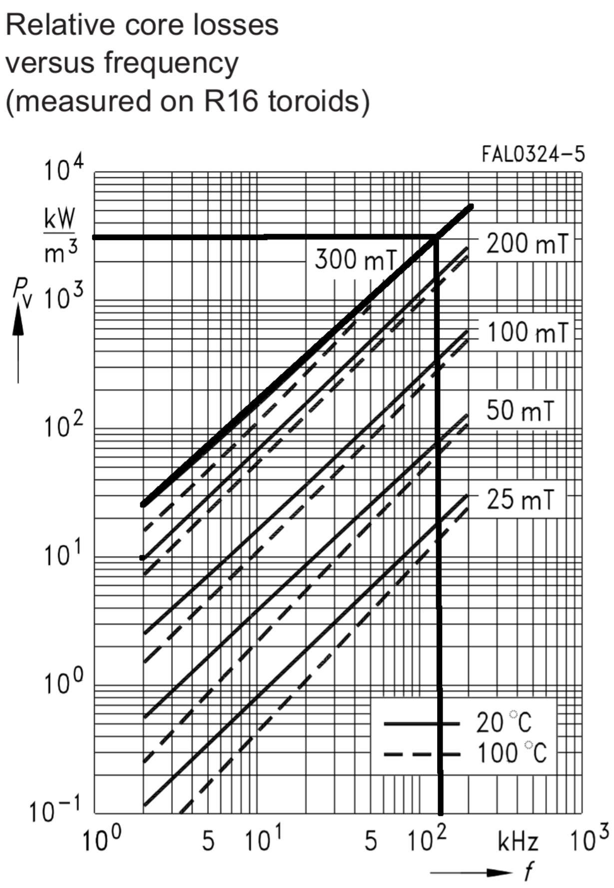
$$
\begin{aligned}
K_{u,actual} &= \frac{N_{selected} \cdot A_{w,selected}}{A_{c,min,sel}} \\
&\approx \frac{22 \cdot 0.636\,173\,\mathrm{mm}^2}{71\,\mathrm{mm}^2} \\
&\approx 0.197\,124
\end{aligned}
\tag{14}
$$

K_u = 0.2 | / 3 pt.

Q20: ESTIMATION OF CORE LOSSES

With the help of a core loss density plot provided in the material's data sheet (TDK EPCOS databook p. 62 and 83), estimate the core losses P_{core} of the designed inductor. Note that most of the preselected ferrite cores are available in N27 material. Would you need a more advanced material like N87 for your Boost inductor? Explain your answer. Calculate the percentage of the output power that the losses correspond to.

Figure 1 N27 Losses



$$
\begin{aligned}
P_{core} &= P_{relative,125\,\mathrm{kHz}} \cdot V_e \\
&\approx 3000\,\mathrm{kW\,m^{-3}} \cdot 5.47 \times 10^{-6}\,\mathrm{m} \\
&\approx 0.016\,41\,\mathrm{W} \\
P_{core,\%} &= \frac{P_{core}}{P_{out,nom}} \cdot 100 \\
&\approx \frac{0.016\,41\,\mathrm{W}}{50\,\mathrm{W}} \cdot 100 \\
&\approx 0.032\,82\,\%
\end{aligned}
\tag{15}
$$

P_{core} = 0.03 W	which corresponds to	0.03 % of the output power.	/ 6 pt.

Q21: THERMAL CONSIDERATION

Estimate the temperature rise of the designed inductor. 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.

For ETD29/16/10 we have

$$R_{th} = 28\,\mathrm{K\,W^{-1}} \tag{16}$$

Ergo the estimated temperature difference:

$$\Delta T = R_{th} \cdot \left(P_{Cu,DC,nom} + P_{core}\right) \approx 28\,\mathrm{K\,W^{-1}} \cdot (0.173\,497\,\mathrm{W} + 0.016\,41\,\mathrm{W}) \approx 5.3174\,\mathrm{K} \quad (17)$$

$\Delta T =$ 5.3 K

/ 3 pt.

Q22: BOOST INDUCTOR DESIGN SUMMARY

Fill Table 7 given below with your design results. Do not forget to include the units.

Table 7 Boost inductor design summary

Electrical specification		
Nominal inductance	L_{nom}	230 mH
Effective current	$I_{L,\mathrm{rms}}$	2.379 63 A
Current ripple	$\Delta I_{L,\mathrm{pk-pk}}$	41.8 mA
Ripple frequency	f_{sw}	125 kHz
Core specification		
Core shape and size		EDT29/16/19
Coil former		B66359X1014T00
Core material		N27
Peak flux density	B_{pk}	350 mT
Air gap length	l_{g}	0.2 mm
Winding specification		
wire diameter	$\varnothing$	0.9
number of turns	N	22
Losses and temperature rise		
Core losses	P_{core}	0.03 W
Winding losses	$P_{\mathrm{Cu,dc}}$	0.2 W
Total inductor losses	$P_{\mathrm{L,loss}}/P_{\mathrm{out}}$	0.26 %
Temperature rise	ΔT	5.3 K

/ 1 pt.

Q23: BOOST CONVERTER EFFICIENCY

Taking into account the input voltage dependency of the semiconductor losses, estimate the best and the worst overall efficiency of your Boost converter for the nominal output power taking the inductor losses into account .

$$
\begin{aligned}
P_{inductance,nom} &= P_{Cu,DC,nom} + P_{core} \\
&\approx 0.173\,497\,\mathrm{W} + 0.016\,41\,\mathrm{W} \\
&\approx 0.189\,907\,\mathrm{W} \\
P_{inductance,max} &= P_{Cu,DC,max} + P_{core} \\
&\approx 0.308\,445\,\mathrm{W} + 0.016\,41\,\mathrm{W} \\
&\approx 0.324\,855\,\mathrm{W} \\
P_{semiconductor} &= P_{T,sw} + P_{T,cond} + P_{D,cond} \\
&\approx 0.525\,\mathrm{W} + 0.4\,\mathrm{W} + 1\,\mathrm{W} \\
&\approx 1.925\,\mathrm{W} \\
\eta_{boost,best} &= \frac{P_{out,nom}}{P_{out,nom} + P_{inductance,nom} + P_{semiconductor}} \\
&\approx \frac{50\,\mathrm{W}}{50\,\mathrm{W} + 0.189\,907\,\mathrm{W} + 1.925\,\mathrm{W}} \\
&\approx 0.959\,418 \\
\eta_{boost,worst} &= \frac{P_{out,nom}}{P_{out,nom} + P_{inductance,max} + P_{semiconductor}} \\
&\approx \frac{50\,\mathrm{W}}{50\,\mathrm{W} + 0.324\,855\,\mathrm{W} + 1.925\,\mathrm{W}} \\
&\approx 0.956\,94
\end{aligned}
\tag{18}
$$

$\eta_{boost,best} =$ 95.9 %

$\eta_{boost,worst} =$ 95.6 %

/ 6 pt.

INDUCTOR MEASUREMENT PROCEDURE

Q24: INDUCTANCE MEASUREMENT AND SOLDERING

Using the BK PRECISION 895 LCR meter (shown on the picture) as a supply connected to the terminals of the inductor, verify that you have achieved the desired inductance value by following the steps below:

- Wind *N* turns on the coil former (for this, use the winding machine)
- Assemble the core (first without the second yoke)
- Set the frequency on the RLC meter to the operating frequency of your converter
- Measure the inductance value
- If the inductance value is too high, apply Kapton tape and repeat the previous step until reaching the desired inductance
- Apply the second yoke. Bear in mind that this will compress the Kapton tape layers, effectively decreasing the air gap length and again slightly increasing the inductance
- Solder the windings to the respective pins of the coil former and provide 3 pictures (from different angles) of the the final soldered inductance. When soldering, please be aware that the pins are fragile and break easily. Measure the inductance value again. If necessary, make adjustments.

Provide a picture of the choke connected to the RLC meter, with the display showing the inductance value clearly visible.

Figure 2 Inductance measurement

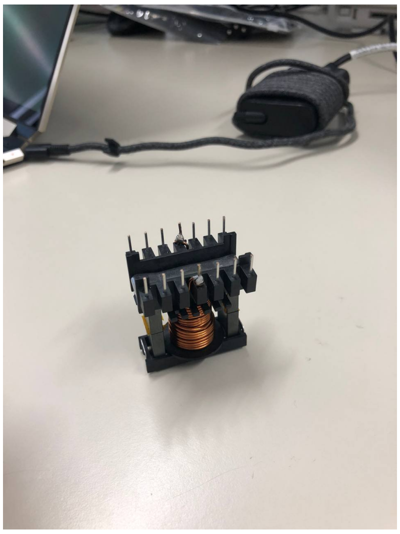


Figure 3 angle 1

Figure 4 angle 2

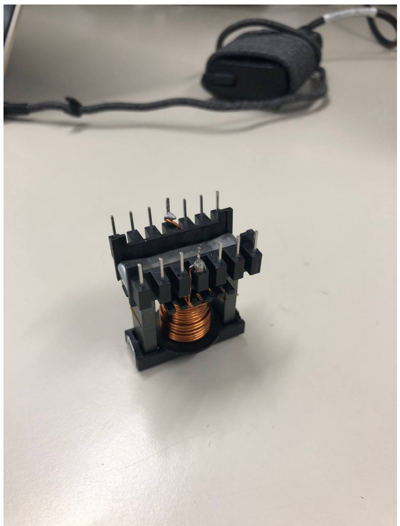


Figure 5 angle 3

/ 4 pt.

Q25: SATURATION MEASUREMENTS

Using the Power Choke Tester DPG10 (shown on the picture), execute the saturation test by following the steps below:

- Connect both the Force and Sense cable to the power choke meter and to the terminals of the choke
- Once connected, cover the inductor with Plexiglas box and do not touch until the end of the measuring process
- The max current value corresponds to your inductor peak current
- The measured voltage value corresponds to your peak-to-peak inductor voltage (see Plecs model)
- For the pulse time enter 10ms
- Enter N and A_{eff} for $L(I)$ to $B(I)$ conversion

Verify that your core is not saturating and provide the $L(I)$ curve (showing both the incremental and the secant inductance) and $B(I)$ curve as well as a picture of the measuring setup.

the maximum inductor current that we can have is 3,2A. Therefore, we can see that with our inductor we're still in the linear zone and not saturating. Moreover, we always need an inductor of a value superior to 140 μH and we see that this value is respected even with the value of 3,2A.

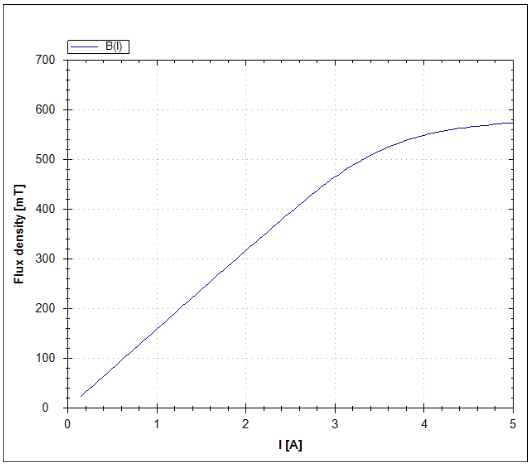


Figure 6 Measurement setup

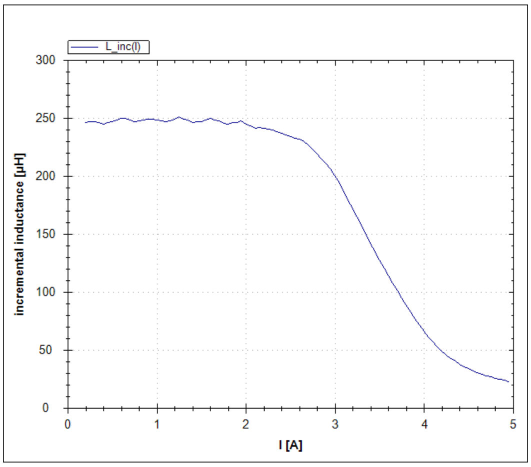


Figure 7 Impedence measurement

Figure 8 Impedence measurement

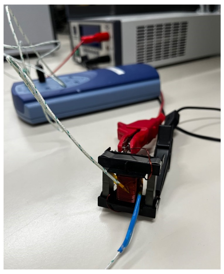
/ 4 pt.

Q26: HEAT-RUN TEST

Using the provided power supply, execute a heat-run test following these steps:

- Connect the power supply to the the inductor terminals using the following settings: 5V output voltage and inductor rms current as a current reference
- Connect two thermocouple probes to the inductor: one on the outside of the winding, one between the winding and the core.
- Once the temperature rise reaches saturation (e.g. after 15 min) take a picture of the inductor with a thermal camera.

Provide a picture of the test-setup, the two temperature rise curves and the thermal image.



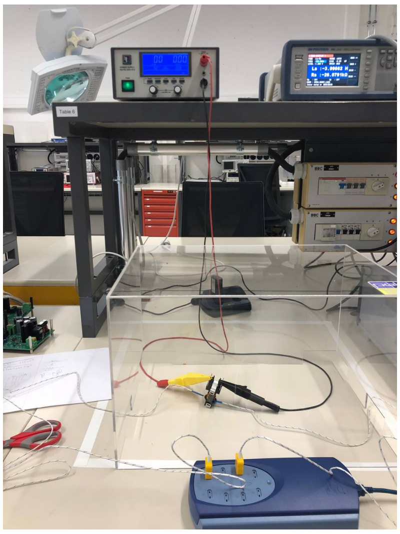


Figure 9 setup

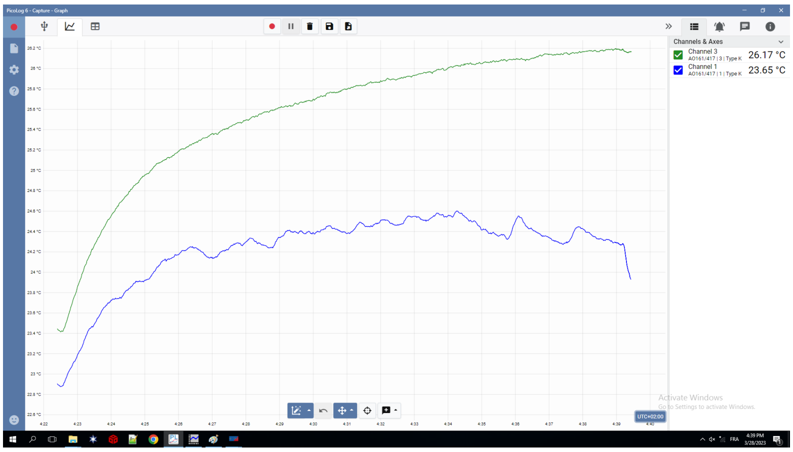


Figure 10 temperature rise curve

Figure 11 pre-measure

Figure 12 post-measure

T_{init} = 24.9 °C	T_{final} = 28.5 °C	/ 4 pt.

Q27: IMPEDANCE AND RESONANT FREQUENCY MEASUREMENT

Using the Omicron Lab Bode 100, execute the measurement by following the steps below:

- Start a new Impedance analysis (One-Port)
- Run a single measurement in the range of 1 Hz to 40 MHz
- Write down the impedance magnitude and phase values as well as the self resonance frequency of the inductor and include them in the report

Provide a picture of the setup as well as a screenshot of the impedance measurement showing impedance magnitude and phase.

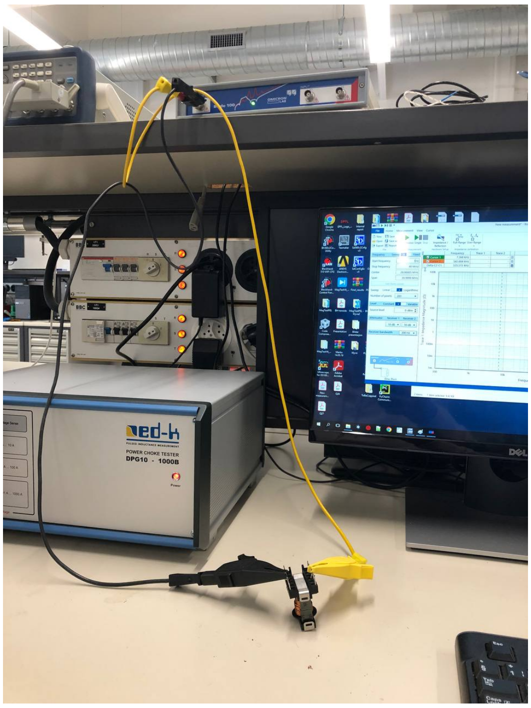


Figure 13 Measurement setup

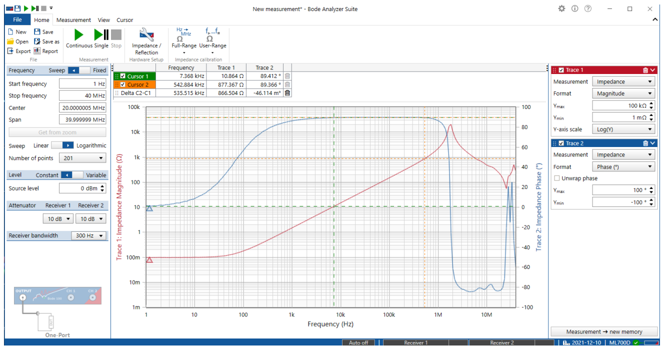


Figure 14 Impedence measurement

the impedance magnitude is 180 Ω and its phase is 90 °. Moreover, the self resonance frequency is 1,8 MHz.

/ 4 pt.

SELECTION OF INPUT AND OUTPUT CAPACITORS

Q28: SELECTION OF THE OUTPUT CAPACITOR

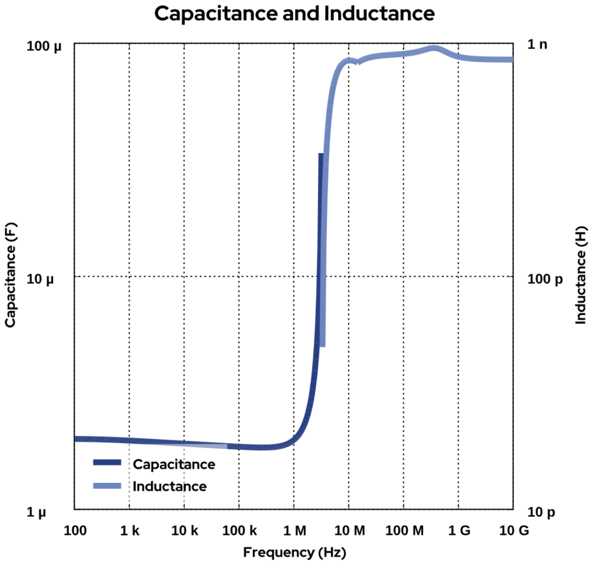
Select the output capacitor (ceramic type MLCC X7R or electrolytic type), so that its rated capacitance (minus tolerance) is higher than C_{min} and the rated voltage of the capacitor is higher than V_{out}. Consider the following in case of ceramic capacitor:

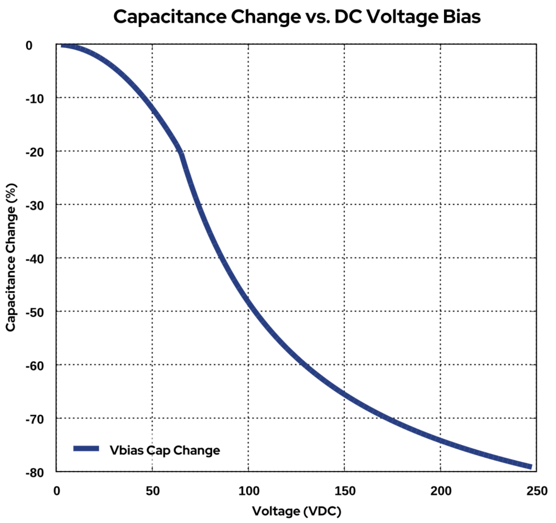
a) De-rate the capacitor according to the DC bias, V_{out}, using curves provided in the capacitor's data sheet;
b) De-rate the capacitor for the operating frequency f_{sw}.

If the de-ratings lead to actual capacitance being lower than C_{min}, choose a higher capacitance. If needed, use a parallel connection of multiple capacitors to realize the needed capacitance, or combine electrolytic and ceramic capacitors.

C2220C205KARLCAUTO

Figure 15 C2220C205KARLCAUTO derating curves





$$
\begin{aligned}
C_{out,min} &\approx 2.5\,\mu\text{F} \\
C_{out,sel} &= 2\,\mu\text{F} \\
C_{out,sel,125kHz} &\approx 1.9\,\mu\text{F} \\
C_{out,sel,derated} &= C_{out,sel,125kHz} \cdot \eta_{derating} \\
&\approx 1.9\,\mu\text{F} \cdot 0.85 \\
&\approx 1.615\,\mu\text{F}
\end{aligned} \tag{19}
$$

By using at least two Capacitors in parallel we have:

$$
\begin{aligned}
N_{C,out} &= \left\lceil \frac{C_{out,min}}{C_{out,sel,derated}} \right\rceil \\
&= \left\lceil \frac{2.5 \times 10^{-6}\,\text{F}}{1.615 \times 10^{-6}\,\text{F}} \right\rceil \\
&= 2 \\
C_{out,effective} &= C_{out,sel,derated} \cdot N_{C,out} \\
&\approx 1.615\,\mu\text{F} \cdot 2 \\
&\approx 3.23\,\mu\text{F}
\end{aligned} \tag{20}
$$

C_{out} = 3.23 µF	Capacitor Type: Ceramic	Reference: C2220C205KARLCAUTO	Package: 2220 (5650 metric)	/ 5 pt.

Q29: ESR OF THE OUTPUT CAPACITOR

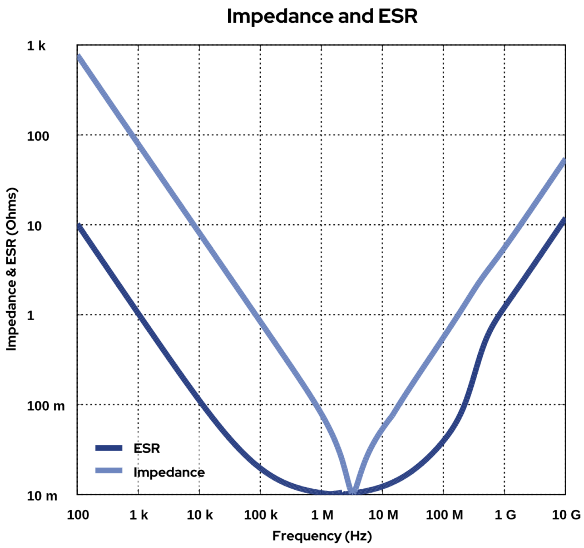
Determine the maximum allowed equivalent series resistance (ESR) for the assigned output voltage ripple and the current ripple (see Part 1). Once the value is determined, check if the selected capacitor has a lower ESR value than the calculated limit. For calculations, you can use the analytical approach or the PLECS model from Part 1 along with appropriate explanations.

The ESR value is either found in the data sheet, or calculated from the dissipation factor (DF) also found in the corresponding data sheet. Both ESR and DF must be given for high-frequency operation (f_{sw}).

In case the calculated ESR exceeds the limit, re-select the value C_{out} from Q28.

$$
\begin{aligned}
Z_{out} &= \frac{0.05 \cdot U_{out}}{2 \cdot \left(I_{L,peak} - I_{L,avg}\right)} \\
&\approx \frac{0.05 \cdot 48\,\mathrm{V}}{2 \cdot (2.462\,81\,\mathrm{A} - 2.379\,14\,\mathrm{A})} \\
&\approx 14.3421\,\Omega \\
ESR_{max} &= \sqrt{Z_{out}^2 - \left(\frac{1}{2 \cdot \pi \cdot f_{sw} \cdot C_{out,sel}^2}\right)} \\
&\approx \sqrt{14.3421\,\Omega^2 - \left(\frac{1}{2 \cdot 3.141\,59 \cdot 125\,000\,\mathrm{Hz} \cdot 2 \times 10^{-6}\,\mathrm{F}^2}\right)} \\
&\approx 14.3279\,\Omega
\end{aligned} \tag{21}
$$

Figure 16 C2220C205KARLCAUTO ESR curve



$$
ESR_{f_{sw}} \approx 0.05\,\Omega \tag{22}
$$

ESR_{max} = 14.3 Ω	$ESR_{(f_{sw})}$ = 0.05 Ω	/ 5 pt.

Q30: POWER LOSSES OF THE OUTPUT CAPACITOR

For a ceramic output capacitor, calculate the power dissipation of C_{out} based on the calculated ESR and the current that flows through the output capacitor. You may use the PLECS model for current rms calculation or analytical calculations. Check if the selected capacitor can withstand the calculated power losses. The empirically determined power limit for 1210 package ceramic SMD capacitors, is given in Table 8.

For an electrolytic capacitor, check if the output current ripple is below the limit for the selected capacitor. The corresponding data sheet provides high-frequency current ripple limit (usually 100 kHz).

Table 8 Ceramic capacitor power dissipation limits at 20 °C rise above Θ_{amb} = 25 °C (Source: AVX).

Type	Package	Thermal resistance	Power rating
Ceramic	1210	70.9 °C W^{-1}	282 mW

$$
\begin{aligned}
P_{ESR} &= \left(\frac{I_{C,rms}}{N_{C,out}}\right)^2 \cdot ESR_{sel} \\
&\approx \left(\frac{1.180\,94\,\mathrm{A}}{2}\right)^2 \cdot 0.05\,\Omega \\
&\approx 0.017\,432\,7\,\mathrm{W}
\end{aligned}
\tag{23}
$$

P_{ESR} =0.0175W

/ 4 pt.

Q31: ENERGY STORAGE IN THE INPUT CAPACITOR

Calculate the minimal input capacitance $C_{in,min}$ needed to store an energy reserve for uninterrupted operation in case of an input voltage loss for 10 ms, i.e. during half of a 50 Hz period. Suppose that prior to the fault, the converter had been operated at rated power and an input voltage of $V_{in} = \frac{V_{in,max}+V_{in,min}}{2}$. The input capacitor voltage must not drop below $V_{in,min}$ during the fault.

$$
\begin{aligned}
C_{in,min} &= \frac{P_{out,nom} \cdot t_{survival}}{0.5 \cdot \left(U^2_{in,nom} - U^2_{in,min}\right)} \\
&\approx \frac{50\,\mathrm{W} \cdot 0.01\,\mathrm{s}}{0.5 \cdot \left(21\,\mathrm{V}^2 - 15.75\,\mathrm{V}^2\right)} \\
&\approx 0.005\,183\,03\,\mathrm{F} \\
C_{in,min} &\approx 5.183\,03\,\mathrm{mF}
\end{aligned}
\tag{24}
$$

$C_{in,min}$ = 5,2 mF

/ 5 pt.

Q32: SELECTION OF THE INPUT CAPACITOR

Select the input capacitor of electrolytic or ceramic type (X7R), so that the operating voltage is above $V_{in,max}$ and the capacitance is above $C_{in,min}$. Consider the following:

a) In case of ceramic capacitor, de-rate the capacitance according to the DC bias of $V_{in,max}$, using curves provided in the capacitor's data sheet;

b) In case of ceramic capacitor, de-rate the capacitance for the operating frequency f_{sw}.

If the de-ratings lead to actual capacitance being lower than $C_{in,min}$, choose higher capacitance or use multiple capacitors in parallel.

we need an input capacitor of at least 5,2 mF. Therefore, we'll put in parall two capacitors of 3,3 mF

C_{in} = 6,6 mF | Code: ECA-1HHG332 | Package:

/ 5 pt.