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Title

R3: LLC HALF-BRIDGE RESONANT CONVERTER - SCHEMATIC AND PCB DESIGN

Course Name

EE-365 Power Electronics

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TABLE OF CONTENTS

OVERVIEW

In the third part, the project course deals with the schematic and PCB design of the LLC Half-Bridge Resonant Converter according to the specifications assigned to your group. Furthermore, the selection of all the necessary components will be made and used to fill out the provided schematic and PCB layout template in ALTIUM.

The list of available SMD capacitors, SMD resistors and THT trimmers that can be used for your design is provided in the Appendix section. The use of additional components not listed in the Appendix is allowed for some specific elements, but it needs to be properly motivated and authorized. See the Appendix section for further information.

To provide your answers and explanations, use the framed boxes below each question.
Follow the nomenclature given in this report to set the proper designators for the circuit components.
In case multiple units are employed to realize the same circuit component, append additional frame boxes in the answers, and add numbers to the corresponding designators (e.g., in case of multiple parallel input capacitors, denote them as $C_{in,1}$, $C_{in,2}$, ect...).

Populate the schematic diagram while proceeding from Q1 to Q23. Complete and review the schematic diagram in Q25 and finally proceed to the design of the PCB. Some hints are provided along the text to facilitate the design process.

As a first step, create the ALTIUM schematic diagram and start placing the MOSFET, the Schottky Diodes, the input and output terminal connectors and the template model of the LLC transformer.

For some capacitors and resistors you will sometimes find that the calculated value does not match the commercially available values. In this case, you can select the closest value to the theoretical value from the list of available resistors and capacitors (see the tables 2 and 3) and check your calculations to see if this value still meets your requirements. You can also make series, parallel or series-parallel arrangements to achieve the target value, but only arrangements of a maximum of two or three elements are allowed. Avoid a series arrangement of capacitors as there will always be complications with voltage sharing across the capacitors.

For resistor series arrangements, the equivalent resistance R_{eq} is the sum of all the resistors connected in series (view Fig.1):

$$R_{eq} = R_1 + R_2 + ... + R_n.$$

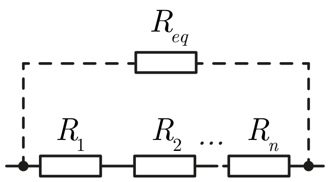

Figure 1 Series arrangement of resistors.

For resistor parallel arrangements (view Fig.2), the equivalent resistance can be computed as follows:

$$R_{eq} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + ... + \frac{1}{R_n}},$$

while for parallel capacitor arrangements, the equivalent capacitance is simply the sum of the capacitances connected in parallel:

$$C_{eq} = C_1 + C_2 + ... + C_n.$$

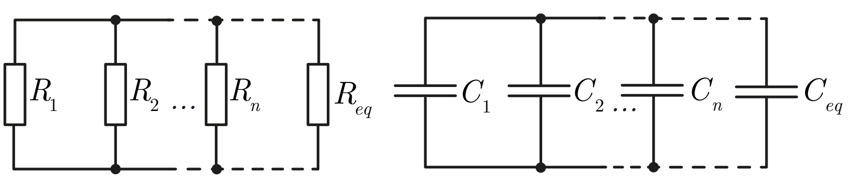

Figure 2 Parallel arrangement of resistors and capacitors.

SELECTION OF THE INPUT AND OUTPUT CAPACITORS

This section focuses on the choice of the Input and Output capacitors, and on the corresponding discharge resistors.

Q1: SELECTION OF THE OUTPUT CAPACITOR

Select the output capacitor so that its rated capacitance (minus tolerance) is higher than $C_{out,min}$ (extracted empirically in Report 1). For safety reasons, the rated voltage of the capacitor must be higher than the maximum output voltage including the maximum ripple voltage (use a safety margin of at least 20%).

Consider the following in case of ceramic capacitor:

a) De-rate the capacitor according to the DC bias, U_{out}, using curves provided in its datasheet;
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, or combine different kind of capacitors (e.g., electrolytic and ceramic).

ALTIUM Schematic Hints:
Connect the capacitor in parallel to the output connector. Respect the correct polarity. Use the designator C_{out}.

From Report 1, $C_{out,min} = 1.5\mu F$. Additionally, the maximum output voltage is $V_{max} = 26.43\,\text{V}$, so with a safety margin of 20% the output capacitor must be rated for at minimum $V_{safe} = V_{max} \times 1.2 = 26.43\,[\text{V}] \times 1.2 = 31.72\,[\text{V}]$.

We choose ceramic capacitor C1825C225J5RACTU, which has a capacitance of $2.2\mu F$, a tolerance of 5%, and a voltage rating of $50\,\text{V}$. From the capacitor's simulation of Capacitor Change versus Bias Voltage, it can be seen that at $26.43\,\text{V}$, the DC bias is 21% and at f_{res} the simulation has an impedance that gives $c = \frac{1}{\omega z} = \frac{1}{2\pi f z} = \frac{1}{2\pi \times 385\,[\text{Hz}] \times 201.7\,[m\Omega]} = 2\mu F$. Therefore, the capacitor is de-rated as follows:

$$C_{out,derated} = C_{out} \times (1 - 0.05) \times (1 - 0.21) = 2\mu F \times (1 - 0.05) \times (1 - 0.21) = 1.5\mu F$$

We verify that $C_{out,derated}$ meets our required capacitance, and that the selected capacitor's voltage rating is greater than our required V_{safe}.

$C_{out} = 2.2\mu F$	Code: C1825C225J5RACTU	Package: 1825/4564	/ 5 pt.

Q2: ESR AND IMPEDANCE OF THE OUTPUT CAPACITOR

Using the datasheet of the chosen capacitor, compute the equivalent series resistance (ESR), and the equivalent impedance $Z_{C,out}$ at the converter highest switching frequency (resonant frequency, f_{res}).
In case of multiple parallel connected capacitors, take into account their mutual contributions during the calculations.

For electrolytic models, the ESR is typically calculated from the dissipation factor (DF) provided in the datasheet. Both ESR and DF must be given for the highest frequency operation (f_{res}). For the computation of the equivalent impedance, consider the possible variation of the capacitance with the frequency.

From the capacitor's simulation of the Impedance & ESR versus Frequency, at $f_{res} = 385\,\text{kHz}$, $ESR_{C,out}(f_{res}) = 19.73m\Omega$ and $Z_{C,out}(f_{res}) = 201.70m\Omega$. As we are using a single capacitor, there are no mutual contributions to consider.

$ESR_{C,out}(f_{res}) =$ 19.73$m\Omega$	$Z_{C,out}(f_{res}) =$ 201.70$m\Omega$	/ 5 pt.

Q3: CURRENT RIPPLE AND POWER VERIFICATION OF THE OUTPUT CAPACITOR

Compute the steady-state RMS current in the capacitor in the worst case conditions. Then, assuming this current is sinusoidal at f_{res}, check if this current ripple can be sustained by the selected capacitor. In case it exceeds the limit, re-select a capacitor model from Q1, or consider using a parallel connection of multiple units. In case of multiple parallel connected capacitors, check this limit for all the selected units.

Then, compute the power $P_{ESR,out}$ dissipated in the capacitor ESR.

Hints:
In case of electrolytic capacitors, the datasheet typically provides high-frequency current ripple limit (usually 100 kHz). In case of ceramic capacitors, the data-sheet typically provides a graph of the current ripple that can be sustained at different frequencies. In

case this information is missing, the ripple current can be checked from the power $P_{ESR,out}$ itself.

From our PLECS simulation, our worst case conditions occur at minimum frequency, where the current ripple is around 4.7 A. Referencing this against the capacitor simulation, the corresponding temperature rise remains in the acceptable green region.

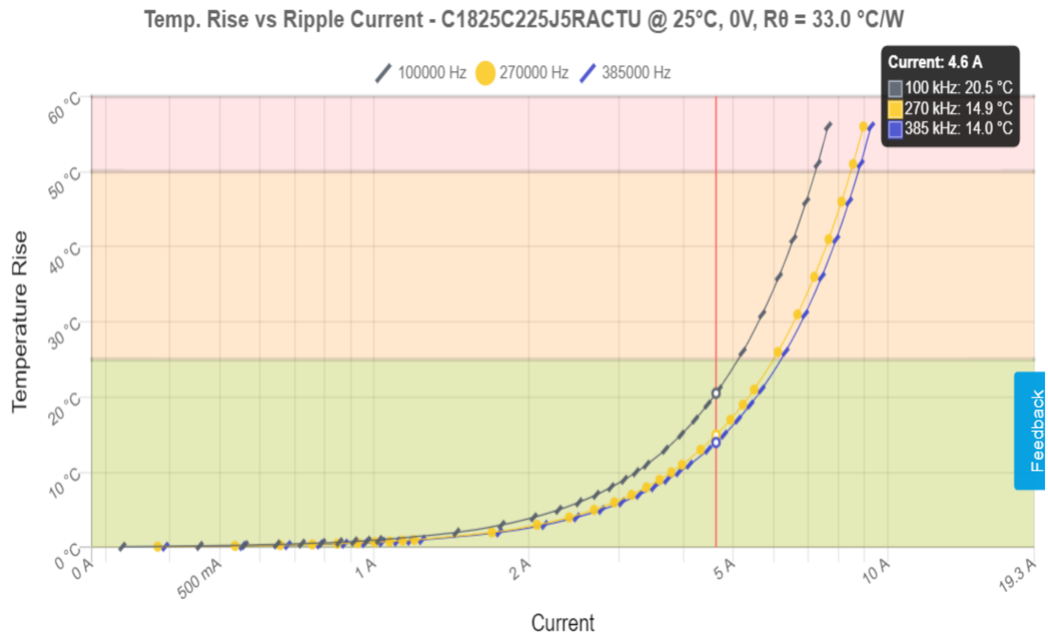

Figure 3 Temp rise un function of current ripple for C1825C225J5RACTU

To calculate the power dissipated: from our PLECS simulation $I_{RMS,C_{out}}(f_{min}) = 1.7\,\text{A}$. From Q2, $ESR_{C,out}(f_{min}) = 21.1m\Omega$. Therefore, $P_{ESR,out} = I_{RMS,C_{out}}(f_{min})^2 \times ESR_{C,out} = 1.7\,\text{A}^2 \times 0.0211\Omega = 0.061\,\text{W}$.

$I_{RMS,C_{out}} = 1.7A$ | $P_{ESR,out} = 0.061W$ | / 5 pt.

Q4: VOLTAGE RIPPLE VERIFICATION OF THE OUTPUT CAPACITOR

Assuming, as in Q3 that the ripple current is sinusoidal at f_{res}, compute the voltage ripple of the output capacitor (taking into account the effect of the ESR).
Verify if this voltage ripple is coherent with the specifications of the LLC converter.
In case it exceeds the limit, re-select a capacitor model from Q1.

From our PLECS simulation, the voltage ripple of the output capacitor is 0.73 V. This is less than the LLC voltage ripple requirement of 1.2 V, from Report 1.

$U_{out,pp} = 0.73V$ | / 5 pt.

Q5: SELECTION OF THE INPUT CAPACITOR

Select the input capacitor in a way that the operating voltage is above $U_{in,max}$ (use a safety margin of at least 20%) and the capacitance is above $C_{in,min}$ (computed in Part 1).

If the de-ratings considering tolerance variations lead to actual capacitance being lower than $C_{in,min}$, choose a higher capacitance. If needed, use a parallel connection of multiple capacitors, or combine different kind of capacitors (e.g., electrolytic and ceramic).

ALTIUM Schematic Hints:
Connect the capacitor in parallel to the input connector. Respect the correct polarity. Use the designator C_{in}.

From Report 1, $C_{in,min} = 2.35mF$. The operating voltage should be above $U_{in,max} = 50\,[\mathrm{V}] \times 120\,\% = 60\,[\mathrm{V}]$.

As our $C_{in,min}$ value is high for a capacitor, we chose to select one electrolytic capacitor with a capacitance of $2700\mu F$ and a voltage rating of $63\,\mathrm{V}$. The tolerance of the capacitor is $20\,\%$, so the worst case value of the capacitor is $C_{in,derated} = 2700\mu F \times 80\,\% = 2.160\mu F$.

$C_{in} = 2700\mu F$	Code: EKMH630VSN272MQ35S	Package: N/A	/ 3 pt.

Q6: DISCHARGE RESISTORS

Calculate the maximum resistance $R_{in,max}$ that will discharge the selected input capacitor within 1 minute (from the initial voltage to less than 5%).

Then, select the resistor to use in the real circuit from standard available values. Furthermore, calculate power losses in the input resistor during normal operation (for the input discharge resistor consider the maximum voltage $U_{in,max}$). Select resistors with power ratings at least two times higher than the calculated loss values.

<u>ALTIUM Schematic Hints:</u>
Connect the discharge resistors in parallel to the input capacitor. Use the designators R_{in}.

<u>ALTIUM PCB Hints:</u>
Increase the pad size of the resistor footprint to provide thermal relief to the package.

The voltage of a capacitor as it discharges is as follows.

$$U_c = U_o \times e^{\frac{-t}{RC}}$$

Here, U_c should be 5% of U_o, $t = 60$ seconds, and $C = 2.352mF$. Then,

$$0.05 \times U = U \times e^{\frac{-60s}{R_{in,max}(2.352mF)}} \Rightarrow R_{in,max} = 8515.5153 = 8.52k\Omega$$

Therefore

$$R_{in} < 8.52k\Omega$$

.

We chose two $3.3k\Omega$ resistors in series to obtain a resistance such that the discharge time is close to one minute. Also, The power loss is then calculated:

$$P_{R,in} = \frac{V^2}{R_{in}} = \frac{(50\,[\mathrm{V}])^2}{6.6[k\Omega]} = 0.38[W]$$

Therefore, our resistors must have a power rating higher than $0.38\,[\mathrm{W}] \times 2 = 0.76\,[\mathrm{W}]$.

$R_{in,max} = 8.52k\Omega$	$R_{in,1} = 6.6k\Omega$	$P_{R,in} = 0.38W$	Code: 2x CRGP2512F3K3	Package: 2512/6332	/ 3 pt.

CONTROLLER CONFIGURATION

For the converter control, the resonant controller L6599A of STMicroelectronics will be used. A diagram of the corresponding IC is given in Figure 4. A more detailed block diagram of the selected controller can be found in the application note *L6599A - Improved high-voltage resonant controller* .

This section is aimed at specifying the preliminary settings for the desired IC configuration.

<u>ALTIUM Schematic Hints:</u>
Place the L6599A controller in your ALTIUM schematic. Choose the DIP16 through-hole socket footprint (you can find the footprint in the provided template).

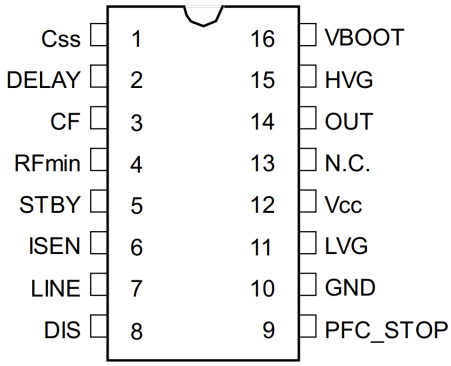

Figure 4 Pinout of L6599A.

Q7: MINIMUM FREQUENCY OSCILLATOR SETTING

The oscillator is programmed externally by means of a capacitor C_F, connected from pin 3 (CF) to ground, that is alternately charged and discharged by the current defined with the network connected to pin 4 (RFmin).

The first step is to set C_F in the hundred pF or in the nF (consistently with the maximum source capability of the RFmin pin and trading this off against the total consumption of the device) (check *L6599A - Improved high-voltage resonant controller*).
Then, calculate the value of $R_{F_{min}}$ that guarantees the minimum operating frequency. You can find support on the graph provided in the application note *L6599A - Improved high-voltage resonant controller* (Section 6).
Next, select a standard resistor and capacitor value and recalculate the minimum frequency for the worst case, taking into account the tolerance variation. Check that your worst case recalculated frequency does not fall below the target frequency. If it does, select your resistor and/or capacitor again.

ALTIUM Schematic Hints:
Connect the capacitor C_F between the CF and GND pins, and the resistor $R_{F_{min}}$ between the RFmin and GND pins. Use the designators $R_{F_{min}}$ and C_F. Consider adding an auxiliary trimmer for $R_{F_{min}}$ to allow for possible adjustments.

ALTIUM PCB Hints:
For best performance, keep the timing capacitor connection as short and direct as possible to the IC.

In the IC datasheet, the electrical characteristics are provided at $C_F = 470pF$, so we set our C_F at the same value. Then,

$$R_{F_{min}} = \frac{1}{3 \times C_F \times F_{min}} = \frac{1}{3 \times 470[pF] \times 270[kHz]} = 2.617[k\Omega]$$

So, we took a resistor of $2.61k\Omega$, which gives our worst case recalculated frequency at $269kHz$.

$R_{F_{min}} = 2.61k\Omega$ | Code: RMCF1206FT2K61 | Package: 1206/3216

$C_F = 470pF$ | Code: C1206C471J5GAC | Package: 1206/3216 | / 5 pt.

Q8: BURST MODE: OPERATION AT NO LOAD OR VERY LIGHT LOAD

The L6599A can be operated in burst mode by using pin 5 (STBY). In this case, the converter gradually reduces the switching frequency by adding idle periods until it enters in standby mode. In essence, $R_{f_{max}}$ defines the maximum switching frequency f_{max} in which the L6599A enters in burst mode operation. Here, f_{max} is associated to some load P_{out_B} greater than the minimum one. P_{out_B} is such the transformer peak currents are low enough not to cause audible noise.

Calculate the resistor for the maximum allowable frequency operation before the converter enters in burst mode.
Then, assign a value for the resistors R_A and R_B, so that $R_A + R_B$ is much higher than R_C.
Finally, select the STBY capacitor. To choose this capacitor, refer to *L6599A - Improved high-voltage resonant controller*.

Hints:
You can start assuming R_B to be between 50-100 times bigger than R_A, being R_A in the range of 4.7-10$k\Omega$. These values can be adjusted later on empirically with the right amount of correction $R_A/(R_A + R_B)$ needed to minimize the change of P_{out_B}.
R_C and R_D are the same resistors as R_H and R_L, referred in Q14.

ALTIUM Schematic Hints:
Connect R_A and R_B as shown in Fig. 24 (b) in *L6599A - Improved high-voltage resonant controller*. Use the designators R_A and R_B. Connect the bypass capacitor between the STBY and GND pin. Use the designator C_{STBY}.

ALTIUM PCB Hints:
For best performances, use a short lead path. Place the C_{STBY} capacitor as close to the IC as possible to reduce switching noise pick-up, this will help obtain clean operation.

First,

$$R_{F_{max}} = \frac{3}{8}\frac{RF_{min}}{\frac{f_{max}}{f_{min}} - 1} = \frac{3}{8}\frac{2.61[k\Omega]}{\frac{385\,[\mathrm{kHz}]}{270\,[\mathrm{kHz}]} - 1} = 2.327k\Omega$$

Therefore we take a resistance of $2.32[k\Omega]$.

To start we take $R_A = 7.5k\Omega$ then $R_B = 59k\Omega$, and an STBY capacitor with a capacitance of $100pF$.

$R_{F_{max}} = 232k\Omega$	Code: RMCF1206FT2K32	Package: 1206/3216	
$R_A = 7.5k\Omega$	Code: RMCF1206FT7K50	Package: 1206/3216	
$R_B = 590k\Omega$	Code: RMCF1206FT590K	Package: 1206/3216	
$C_{STBY} = 100pF$	Code: C1206C101J1GAC7210	Package: 1206/3216	/ 5 pt.

Q9: SOFT-START MODE

Generally speaking, the purpose of soft-start is to progressively increase converter power capability when it is started up, so as to avoid excessive inrush current. Initially, the capacitor C_{ss} is totally discharged, so that the series resistor R_{ss} is effectively in parallel to $R_{F_{min}}$ and the resulting initial frequency (F_{start}) is determined by R_{ss} and $R_{F_{min}}$.

For this calculation, pick the selected value of the standard resistor $R_{F_{min}}$ from Q7 and calculate the soft-start resistor R_{ss}, taking into account the value of your minimum frequency (F_{min}) and your initial frequency (F_{start}).
Then, calculate the value of the soft-start capacitor C_{ss}. Then select the standard values for both your resistor and capacitor and recalculate the soft-start frequency for the worst case tolerances to check that F_{start} is within the range. If it is not the case, select your resistor and/or capacitor again.

Hints:
It is recommended that F_{start} be four times the minimum frequency (F_{min}); however, if your resonant frequency is close to the maximum operating frequency of the L6599A controller, you can set F_{start} below the maximum frequency but at the same time something above your resonant frequency.

ALTIUM Schematic Hints:
Connect the soft-start capacitor C_{ss} between the Css and GND pins, and the resistor R_{ss} between the Css and RFmin pins. Use the designators R_{ss} and C_{ss}.

As our minimum frequency is high we need to take a starting frequency close to the maximum frequency of the oscillator. We choose $f_{start} = 480kHz$, then from the datasheet:

$$R_{SS} = \frac{R_{Fmin}}{\frac{f_{start}}{f_{fmin}} - 1} = \frac{2.61[k\Omega]}{\frac{480[kHz]}{270[kHz]} - 1} = 3.384[k\Omega]$$

We therefore choose a standard resistor value of $3.4k\Omega$ Then,

$$C_{ss} = \frac{3 \cdot 10^{-3}}{Rss} = \frac{3 \cdot 10^{-3}}{3.4[k\Omega]} = 0.882\mu F$$

So we choose two capacitors in parallel each with capacitance of $0.47\mu F$ for a total capacitance of $0.96\mu F$.

$R_{ss} = 3.4k\Omega$	Code: RMCF1206FT3K40	Package: 1206/3216	
$C_{ss} = 0.47\mu F + 0.47\mu F$	Code: 2xC1206C474K3RACTU	Package: 1206/3216	/ 5 pt.

Q10: BOOSTRAP CIRCUITRY SELECTION

When using half-bridge configurations, it is necessary to generate a high-side bias to drive the gate of the high-side FET with respect to the switch node. One of the most popular and cost-effective ways for designers to do this is to use a bootstrap circuit consisting of a capacitor, diode, resistor and bypass capacitor. The L6599A structure replaces this external diode. It is achieved by a high-voltage DMOS operating in the third quadrant and driven synchronously with the low-side driver (LVG), with a diode in series with the source.

Estimate the voltage drop on the bootstrap driver voltage. Use the maximum gate charge (Q_g) available on your selected MOSFET datasheet and the bootstrap on-resistance of the bootstrap DMOS ($R_{DS_{on}}$). Consider a dead time of $DT = 270ns$ for your calculation. Then calculate the minimum required bootstrap capacitor according to *Bootstrap Circuitry Selection for Half-Bridge Configurations* application note (section 3).
Select a standard value for your bootstrap capacitor (C_{boot}). Check that the capacitance does not fall below the minimum bootstrap capacitance for the worst tolerance variations. If this is the case, select a higher capacitor value.

<u>ALTIUM Schematic Hints:</u>
Connect the bootstrap capacitor between the VBOOT and OUT pins of the L6599A IC. Use the designator C_{boot}.

To calculate the voltage drop:

$$V_{drop} = I_{charge}R_{DS_{on}} + V_F = \frac{Q_g}{T_{charge}}R_{DS_{on}} + V_F = \frac{17\times10^{-9}\,[\mathrm{C}]}{0.5\frac{1}{f_{max}} - DT}R_{DS_{on}} + V_F = \frac{17e-9[C]}{0.5\frac{1}{385[kHz]} - 270[ns]}150[\Omega] + 0.6[V] = 3.0789\,[\mathrm{V}]$$

Then to calculate the bootstrap capacitor:

$$C_{boot} = 10\frac{Q_g}{V_{dd} - V_{drop}} = 10\frac{17\times10^{-9}\,[\mathrm{C}]}{15\,[\mathrm{V}] - 3.0789\,[\mathrm{V}]} = 14.26[nF]$$

We chose a standard capacitor of $18nF$ which has a worst-case value of $17.1nF$, which is above our minimum bootstrap capacitance.

$V_{drop} = 3.08V$	$C_{boot} = 18nF$	Code: C1206C183J5RACTU	Package: 1206/3216	/ 5 pt.

CURRENT AND VOLTAGE PROTECTIONS

The current sensing function in the selected L6599A controller is aimed for overcurrent protection (OCP) only. To provide OCP, the primary peak current must be measured. The current sense network consists of a shunt resistor and a low-pass RC filter. The output signal is provided to the ISEN pin of the L6599a IC. This sensing method is described in section 7.4 in *L6599A - Improved High Voltage Resonant Controller* (Fig.28, scheme a)).

This section is aimed at designing the current measurement network and the line sensing function.

Q11: CURRENT SENSING SHUNT RESISTOR

Calculate the shunt resistor R_S for current measurements, so that the maximum ISEN pin voltage (see the L6599A datasheet) corresponds to less than 90% of the maximum MOSFET drain to source current I_{DS} (see the your MOSFET datasheet). Calculate the power dissipation of the shunt resistor under worst-case operating conditions. Select a resistor with a suitable power rating.

<u>ALTIUM Schematic Hints:</u>
Connect the resistor between the Source terminal of the low-side MOSFET and the input GND. Use the designator R_S. Choose a resistor with a low tolerance (e.g., $\leq 1\%$) and a low dependence on the temperature. This resistor will dissipate a considerable amount of power. It is strongly recommended to select the power rate of at least two times from the one calculated. Also, procure to use wider pads on your footprint so you can offer thermal relief to the resistor package.

<u>ALTIUM PCB Hints:</u>
Increase the pad size of the resistor footprint to provide thermal relief to the package.
If possible, use a short lead path.

First, $I_{DS} = 12[A]$ so we need $I_{DS,safe} = I_{DS} \times 0.9 = 12[A] \times 0.9 = 10.80[A]$. Then,

$$R_s = \frac{4}{I_{DS,safe}} = \frac{4}{10.80[A]} = 0.3704[\Omega]$$

Then, the power dissipated is:

$$P_{R_s} = I^2_{lr,rms} R_s = 3.28\,[\mathrm{A}]^2 \times 0.3704[\Omega] = 3.9846\,[\mathrm{W}]$$

We chose three parallel resistors of value 1.2Ω of power dissipation of 2W and a dependence of 150ppm/C. To note that there exists resistors of less temperature (100 ppm/C) dependency but they weren't in stock in the supplier websites.

$R_S = 3x1.2\Omega$	$P_{R_s} = 3.98W$	Code: 3430H2F1R2TDF	Package: 1020 (Reversed) /2550 (Reversed)	/ 5 pt.

Q12: CURRENT MEASUREMENT FILTERING

Due to the switching behaviour of the converter, the measured current may include undesired spikes. For this reason, a low-pass filter is used. The filter should be fast enough to follow the dynamics of the input current (i.e., around F_{res}), but low enough to neutralize the undesired spikes effects (i.e., at higher frequencies).

First select a standard value for the low-pass filter capacitor C_{LPF} in the order of nF or pF.
Then, assuming a time constant at least time times bigger than the minimum switching frequency of your converter (i.e., $RC \geq 10/F_{min}$), calculate your low-pass filter resistor R_{LPF}.
Then check that the impedance of the filter at F_{res} is sufficiently higher than the shunt resistor R_S, not to alter the power circuit. In case your impedance is significantly low, change the value of the filter capacitor and recalculate your filter resistor.
Include a Bode plot of the designed filter in your answer.

ALTIUM Schematic Hints:
Connect the filter resistor (R_{LPF}) between the sensing terminal of R_S (i.e., connected to the Source terminal of the MOSFET) and the ISEN pin of the L6599A IC. Connect the filter capacitor (C_{LPF}) between the ISEN pin and the GND pin of the L6599A IC. Use the designators R_{LPF} and C_{LPF}.

ALTIUM PCB Hints:
If possible, connect the filtering components far from the power path. Do not use a direct connection between the resistor and the MOSFET source, but rather connect it to the corresponding terminal of R_S.

We select $C_{LPF} = 120pF$. Then,

$$R_{LPF} = \frac{\tau_{min}}{C_{LPF}} = \frac{\frac{10}{f_{min}}}{C_{LPF}} = \frac{\frac{10}{270[kHz]}}{120[pF]} = 307.5[k\Omega]$$

We chose a standard resistor of $301k\Omega$. To check the minimum switching frequency of the converter:

$$F_c = \frac{1}{\tau} = \frac{1}{C_{LPF}R_{LPF}} = \frac{1}{120[pF] \times 301[k\Omega]} = \frac{1}{3.612 \times 10^{-5}\,[\mathrm{s}]} = 27.69[kHz]$$

Then to check the impedance of the filter at resonant frequency:

$$Z = R_{LPF} - \frac{1}{2\pi f_{res} C_{LPF}} i = 301[kHz] - \frac{1}{2\pi \times 385[kHz] \times 120[pF]} i = 301 - 3.44449i[k\Omega] = 301[k\Omega]$$

This is indeed significantly higher than R_s.

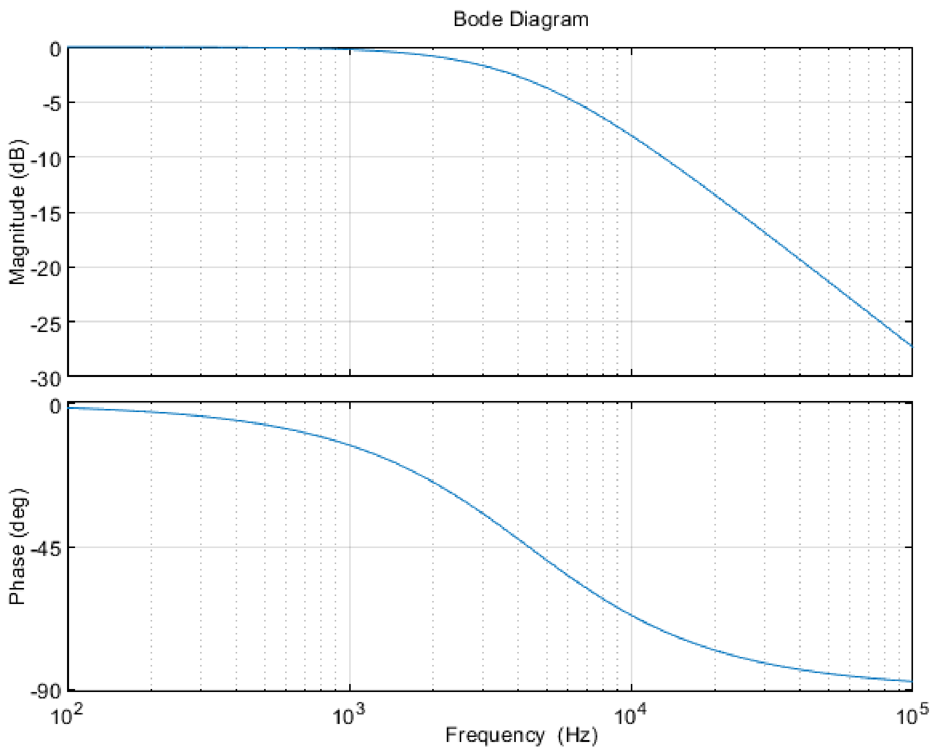

Figure 5 Bode diagram of the transfer function of the current sensing filter.

$R_{LPF} = 301k\Omega$	Code: RMCF1206FT301K	Package: 1206/3216	
$C_{LPF} = 120pF$	Code: C1206C121K5GACTU	Package: 1206/3216	/ 5 pt.

Q13: DELAY SHUTDOWN

In case the converter runs with overload scenarios or short-circuit conditions, the L6599A controller can shutdown and stop the converter's operation. Size the delay capacitor C_{delay} that guarantees that the overload time (T_{SH}) is in the order of 100ms. Then calculate the delay resistor so that the L6599A is shut down for 1s before it softly starts again. For more details, view *L6599A - Improved High Voltage Resonant Controller*.

Hints:
T_{SH} is the time that the converter is allowed to run overloaded or under short-circuit conditions.

ALTIUM Schematic Hints:
Connect the delay capacitor C_{delay} between the DELAY and GND pins, and the delay resistor R_{delay} between the DELAY and GND pins. Use the designators C_{delay} and R_{delay}.

As from datasheet: "As a rough indication, with CDelay = 1 μF, TSH is in the order of 100 ms." Then as the stop times is $T_{stop} = 1s$ we have:

$$R_{delay} = \frac{T_{stop}}{2.5 \cdot C_{delay}} = \frac{1s}{2.5 \cdot 1\mu F} = 400k\Omega \tag{1}$$

We take the closest value for the resistor as $R_{delay} = 392k\Omega$

$R_{delay} = 392k\Omega$	Code: RMCF1206FT392K	Package: 1206/3216	
$C_{delay} = 1\mu F$	Code: C1206C105K3RACTU	Package: 1206/3216	/ 4 pt.

Q14: LINE SENSING FUNCTION

This function essentially stops the IC when the input voltage of the converter falls below the specified range and restarts it when the voltage returns to within the range. This function is performed by a resistive voltage divider consisting of a high-side resistor (R_H) and a low-side resistor (R_L). The midpoint between these two resistors is connected to the LINE pin of the L6599A IC.

Calculate both resistors using an ON threshold voltage of $V_{in_{on}} = 35V$ and an OFF threshold voltage of $V_{in_{off}} = 30V$.
Select your resistors according your calculations.

ALTIUM Schematic Hints:
Choose a resistor with a low tolerance (e.g., 1%) and a low dependence on the temperature.

From the datasheet:

$$R_H = \frac{V_{in,on} - V_{in,off}}{13 * 10^6} = \frac{35 - 30V}{13 * 10^6} = 384.6k\Omega \qquad R_L = R_H \cdot \frac{1.24}{V_{in,off} - 1.24} = 384.6k\Omega \cdot \frac{1.24}{30 - 1.24} = 16.58k\Omega \tag{2}$$

Then we take the resistors of $R_H = 383k\Omega$ and $R_L = 16.5k\Omega$ of 1% tolerance. Which in turn gives us: $V_{in,on} = 35.002V$ and $V_{in,off} = 30.023V$

$R_H = 383k\Omega$	Code: RMCF1206FT383K	Package: 1206/3216	
$R_L = 16.5k\Omega$	Code: RMCF1206FT16K5	Package: 1206/3216	/ 3 pt.

SUPPLY CIRCUIT FOR THE CONTROLLER

The L6599A IC gets power from the Vcc pin. This power supply is provided by a zener network which is composed of a resistor connected in series to the cathode of a zener diode.
This section is aimed at the design of the supply circuit for the L6599A controller.

Q15: AUXILIARY ZENER RESISTOR

The Zener diode must be able to regulate between 30V and 50V and withstand the power dissipation in the worst case.

Calculate the maximum zener resistance $R_{Z_{min}}$ at which the Thevenin voltage V_Z is equal the zener voltage (i.e, $V_Z = V_{TH} = 15V$). Then, select a smaller standard resistance R_Z value that guarantees that the Thevenin voltage V_{TH} is always higher than the zener voltage V_Z and allows the zener diode to regulate the output at Vcc = 15V within the defined input voltage range for the maximum L6599A operating current (defined in *L6599A - Improved high-voltage resonant controller*).
Verify that at the worst tolerance variation, the conditions explained above remain satisfied. If not, select the zener resistor again.
Calculate the power losses on the zener resistor and select a resistor package with a power rating at least 20% higher than the computed value of the power losses.

We have for the oscillator a max current of 5mA, so for security we take a current of 10mA. Thus: As we want our zener diode to regulate the $Vcc = 15V$

$$P_L = V_L \cdot I_L = 0.15W \qquad R_L = \frac{V_L}{I_L} = \frac{15V}{10mA} = 1500\Omega \qquad V_{TH} = \frac{R_L}{R_L + R_s} \cdot V_s \tag{3}$$

We need to calculate for the worst conditions, then the voltage source gives 30V:

$$R_{s,max} = R_L \cdot (\frac{V_{s,min}}{V_{TH}} - 1) = 1500\Omega \cdot (\frac{30V}{15V} - 1) = 1500\Omega \tag{4}$$

We choose one resistor of $1k\Omega$ of tolerance 5% and power of 2W.
First we check if at worst case we still have the correct resistance:

$$1k\Omega * 1.05 = 1.05K\Omega < R_{s,max} \tag{5}$$

For power (most dissipated power at. $V_s = 50V$) and at worst tolerance:

$$P_{max} = \frac{(V_{s,max} - V_{TH})^2}{R_z} = \frac{(50V - 15V)^2}{1k\Omega \cdot 0.95} = 1.28W \tag{6}$$

With safety of 20%

$$P = P_{max} * 1.2 = 1.54W \quad (7)$$

In the ideal case each resistor should dissipate 1.54W.

$R_{Z_{max}} = 1500\Omega$	$R_z = 1000\Omega$	$P_{R_z} = 1.54W$	Code: SR2512JK-7W1KL	Package: 2512/6332	/ 5 pt.

Q16: AUXILIARY SUPPLY ZENER DIODE

Calculate the power losses on the zener diode and select one from the standard values according to the voltage, current and power dissipation constraints. As before, select a zener package with a power rating at least 20% higher than the computed value of the power losses.

Hints:
Check if one diode from the list of available zener diodes found in the appendix section complies with your requirements.

ALTIUM Schematic Hints:
Connect one of the zener resistor terminals to the high-voltage input bus and the other to the zener cathode. Then, connect the zener anode to GND. The midpoint between the zener resistor and the zener cathode represents the regulated output voltage, so this must be connected to the Vcc pin of the L6599A IC.

$V_z = 15V$ **as defined in the previous question. So then we calculate the current that passes trough the diode as follows:**

$$I_s = \frac{V_{s,max} - V_{TH}}{Rz} = \frac{50V - 15V}{1000\Omega} = 0.035A \quad (8)$$

And from the modeled power of the oscillator we have

$$I_L = 10mA \quad (9)$$

Then the current of the diode is:

$$I_z = I_s - I_L = 0.035 - 0.01 = 0.025A \qquad P_z = I_z \cdot V_{TH} = 0.375W \quad (10)$$

For safety fatcor of 20%

$$P = P_z * 1.2 = 0.45W \quad (11)$$

As the power trough the diode would be too high the we put and resistor of 300Ω in parallel to dissipate this extra power:

$$I_s = \frac{V_{s,max} - V_{TH}}{Rs} = \frac{50V - 15V}{333\Omega} = 0.105A \quad (12)$$

And from the modeled power of the oscillator we have

$$I_L = \frac{V_{TH}}{\frac{R_L \cdot R_L'}{R_L + R_L'}} = \frac{15}{\frac{450 \cdot 300}{R450+300}} = 0.083A \quad (13)$$

Then the current of the diode is:

$$I_z = I_s - I_L = 0.022A \quad (14)$$

Then finally

$$P_z = I_z \cdot V_{TH} = 0.33W \quad (15)$$

$V_Z = 15V$	$P_Z = 0.33W$	Code: 1N5245BTR	Package: N/A	/ 3 pt.

Q17: BYPASS CAPACITOR

Sometimes a small bypass capacitor to GND may be useful to get a clean bias voltage for the signal part of the IC. To choose this capacitor, refer to *L6599A - Improved high-voltage resonant controller*.

ALTIUM Schematic Hints:
Connect the bypass capacitor between the Vcc pin to GND pin.

ALTIUM PCB Hints:
Place the bypass capacitor as close to the IC as possible to reduce switching noise pick-up.

From the datasheet, it is possible to bypass the pin to ground with a small film capacitor (e.g. 1-10 nF) to prevent any malfunctioning of this kind. Then we choose a capacitor of 4.7 nF.

$C_{BYPASS} = 4.7nF$	Code: C1206C472J5GECTU	Package: 1206/3216	/ 1 pt.

GATE DRIVER

The L6599A resonant controller has an internal ground-referenced gate driver, which can be used to directly control the MOSFET through the HVG, LVG and OUT pins. The peak sink current that can be absorbed or supplied at the HVG/LVH pin is limited to 0.8A. For additional information, refer to the application note *L6599A - Improved high-voltage resonant controller* (Section 5).

This section is aimed at defining the parameters of the external gate driver circuitry.

Q18: GATE RESISTOR

The gate resistor defines dynamics of the MOSFET switching. A smaller resistance value results in higher turn-ON and turn-OFF speed and into lower switching losses, but requires a higher peak current to operate.

Compute the minimum value of the external gate resistance $R_{G,min}$ to be added to the circuit in order to limit the peak current of the HVG/LVG pins to its feasible range (i.e., 0.8 A).

Then, select a resistor whose resistance value is higher than $R_{G,min}$.

ALTIUM Schematic Hints:
Connect a gate resistor between the HVG pin and the Gate terminal of the high-side MOSFET. Then connect another gate resistor between the LVG pin and the Gate terminal of the low-side MOSFET. Then connect the OUT pin to the midpoint between the high-side MOSFET Source terminal and the low-side MOSFET Drain terminal. Use the designator R_G.

ALTIUM PCB Hints:
If possible, keep a short path for the gate driver outputs.

From the datasheet we take the max output high voltage $V_{LVGH} = 13.3V$ and an $I_{sinkpk} = 0.8A$. We use the following formula:

$$R_{G,min} = \frac{V_{LVGH}}{I_{sinkpk}} = \frac{13.3}{0.8} = 16.625\Omega \quad (16)$$

Due to power dissipation requirements in Q19, we select a resistor of 20Ω of 0.25 W rated power.

$R_{G,min} = 16.6\Omega$	$R_G = 20\Omega$	Code: RMCF1206FT20R0	Package: 1206/3216	/ 5 pt.

Q19: POWER LOSSES OF THE GATE RESISTOR

Estimate the average turn-on and turn-off currents $I_{avg,ON}$ and $I_{avg,OFF}$ through the gate resistor, using the total gate charge Q_g available in the MOSFET data sheet. Thereby, approximate that all of Q_g is injected and extracted within time intervals $t_D(ON)+t_R$, and $t_D(OFF)+t_F$, which are also available in the data sheet.

Calculate the average power through the external gate resistor R_G, assuming pulses of average currents $I_{avg,ON}$ and $I_{avg,OFF}$ during the above mentioned time intervals. Verify that the resistor chosen in Q18 can tolerate this power dissipation. In case this requirement is not satisfied, choose a different resistor in Q18.

NB: Note that, for this approximate calculation, the currents $I_{avg,ON}$ and $I_{avg,OFF}$ may result to be higher than the previously imposed 0.8 A limit. This results in a more conservative margin for the power losses verification.

Looking at the MOSFET datasheet, we find that the average total gate charge $Q_g = 13\,\text{nC}$, and the average time intervals are $t_{d,ON} = 13\,\text{ns}$, $t_R = 19\,\text{ns}$, $t_{d,OFF} = 18\,\text{ns}$, $t_F = 6\,\text{ns}$. We calculate the average turn-on and turn-off currents as follows:

$$I_{avg,ON} = \frac{Q_g}{t_{d,ON} + t_R} = \frac{13\,[\text{nC}]}{32\,[\text{ns}]} = 0.4063\,[\text{A}]$$

$$I_{avg,OFF} = \frac{Q_g}{t_{d,OFF} + t_F} = \frac{13\,[\text{nC}]}{24\,[\text{ns}]} = 0.5416\,[\text{A}]$$

The greatest power dissipation per resistor therefore happens with the turn-off current and is:

$$P_{R_G} = f_{sw} \cdot R_G \cdot (I^2_{avg,ON} \cdot (t_{d,ON} + t_R) + I^2_{avg,OFF} \cdot (t_{d,OFF} + t_F)) = 385kHz \cdot 20\Omega \cdot (0.4063^2 \cdot (13ns + 19ns) + 0.5416^2 \cdot (18ns + 6ns)) = 0.094\,[\text{W}] \quad (17)$$

$I_{avg,ON} = 0.41A$	$I_{avg,OFF} = 0.54A$	$P_{R_G} = 0.094W$	/ 5 pt.

COMPENSATION NETWORK DESIGN

The LLC converter requires a feedback loop to compensate for output voltage variations. This is achieved by using a compensation network. The compensator consists of an error amplifier that measures the output voltage and detects when the measured value deviates from the target value. When this happens, the comparator triggers and the LED on the optocoupler starts to light up. As the output voltage increases/decreases, so does the LED current, causing the phototransistor to saturate more or less depending on the LED light intensity. As a result, the equivalent resistance that sets the IC frequency changes, resulting in a lower/higher switching frequency.

The closed-loop feedback control of the output voltage is here achieved with a Type II compensation network, built upon:

1. a TL431 shunt amplifier, with the aim to measure and process the output voltage,
2. a Vishay VO617A-3X016 optocoupler, with the aim to provide the desired insulation between the primary and secondary side circuits of the LLC resonant converter,
3. the pin RFmin of the *L6599A - Improved high-voltage resonant controller* integrated circuit, with the aim to apply the control action.

Refer to the circuit scheme shown in *L6599A - Improved high-voltage resonant controller* (figure 32, bottom right corner), the application note of *Demystifying Type II and Type III Compensators Using Op-Amp and OTA for DC/DC Converters* (Section 2, figure 3), the book *Switch-Mode Power Supplies, Second Edition: SPICE Simulations and Practical Designs (chapter 3: FEEDBACK AND CONTROL LOOPS)* and the application note of *The TL431 in the Control of Switching Power Supplies)*.

This section is aimed at the complete design of the compensation network.

Q20: REFERENCE OUTPUT VOLTAGE SETTINGS

The reference output voltage $U_{out,ref}$ is determined by the resistors R_{RH} and R_{RL} connected to the TL431 device. These two resistors make a voltage divider, and the steady-state voltage at their connection point is equal to the internal TL431 voltage (i.e., around 2.5 V). Compute the R_{RH} and R_{RL} values based on the output voltage specification of the converter and on a steady-state current absorption of 1 mA. Then, select the proper resistors.

ALTIUM Schematic Hints:
Use the designators R_{RH} and R_{RL}. Connect the R_{RH} resistor between the positive output terminal and the TL431 Ref pin, and the R_{RL} resistor between the TL431 Ref pin and the output ground. To allow for some small adjustments in the real circuit, consider adding a trimmer in series to R_{RL}.

From the application note:

$$R_{RL} = \frac{V_{internal}}{I_{bridgecurrent}} = \frac{2.5V}{1mA} = 2.5k\Omega \tag{18}$$

$$R_{RH} = \frac{V_{pin1} - V_{internal}}{I_{bridgecurrent}} = \frac{24V - 2.5V}{1mA} = 21.5k\Omega \tag{19}$$

Then the resistor we choose are $R_L = 2.55k\Omega$ and $R_RH = 21.5k\Omega$ of 1% tolerance, which gives us: $V_{internal} \approx 2.55V$

$R_{RH} = 2.55k\Omega$	Code: RMCF1206FT2K55	Package: 1206/3216	
$R_{RL} = 21.5k\Omega$	Code: RMCF1206FT21K5	Package: 1206/3216	/ 5 pt.

Q21: COMPENSATION POLE AND ZERO COMPONENTS

The compensation pole and zero of the controller is set through the resistor R_{COMPz} and capacitor C_{COMPz} connected to the TL431 device. Based on the desired cut-off frequency f_c, choose the proper resistor and capacitors to achieve the desired frequency of the pole and zero.
Then calculate the auxiliary capacitor C_{aux}.

Design Hints:
For your calculations, choose an initial value of $f_c = f_{res}/25$, $f_{p1} = kf_c$, $f_z = f_c/k$, $f_{p0} = f_z/10$, being $k = 4.5$ and then, if needed later on, make adjustments according to the other parameters of the compensation network.

ALTIUM Schematic Hints:
Connect the resistor and capacitor in series with each other, and connect the terminals of the series between the TL431 Ref pin and the TL431 cathode pin. Use the designators R_{COMPz} and C_{COMPz}.

$$f_c = \frac{f_{res}}{25} = 15400 \qquad f_p1 = 4.5 \cdot f_c = 69300 \qquad f_z = \frac{f_c}{4.5} = 3422.22 \qquad f_{p0} = \frac{f_z}{10} = 342,22 \tag{20}$$

Then from application notes:

$$C_{COMPz} = \frac{1}{2\pi f_{p0} R_{RH}} = \frac{1}{2\pi f_z R_{RH}} = 0.18\mu F \tag{21}$$

$$R_{COMPz} = \frac{f_{p0} \cdot R_{RH}}{f_z} = 254.9\Omega \tag{22}$$

$$C_{aux} = \frac{f_z}{2\pi R_{RH} f_{p0} f_p 1} = 9nF \tag{23}$$

Then we take $C_{COMPz} = 2.2nF$, $R_{COMPz} = 2.15k\Omega$ and $C_{aux} = 1.2nF$ with the capacitors of 5% tolerance and the resistor of 1% tolerance.

$R_{COMPz} = 2.15k\Omega$	Code: RMCF1206FT2K15	Package: 1206/3216	
$C_{COMPz} = 2.2nF$	Code: C1206C222K5GEC7210	Package: 1206/3216	
$C_{aux} = 1.2nF$	Code: C1206C122J1GACTU	Package: 1206/3216	/ 4 pt.

Q22: LED RESISTOR

Considering the desired output voltage U_{out}, the typical optocoupler input voltage drop (see the Optocoupler datasheet) and the minimum TL431 anode-cathode voltage (see the TL431 datasheet), compute the maximum voltage drop allowed on R_{LED}. Then, select a proper resistance assuming a LED current in the range [4 mA; 10 mA].

ALTIUM Schematic Hints:
Connect the resistor in series to the optocoupler input. Use the designator R_{LED}.

From the TL432 datasheet, the minmum anode cathode voltage is our reference voltage that in our case is 2.5 V. And from the optocoupler datasheet the forward voltage is $V_{CE} = 1.35V$.

$$V_{LED},_{max} = V_{out} - V_{TL472} - V_{octo} = 24V - 2.5V - 1.35V = 20.15V \quad (24)$$

Then:

$$V_{LED},_{max} = I_{LED} \cdot R_{LED},_{max} = [4, 10]mA \cdot R_{LED},_{max} \rightarrow R_{LED},_{max} = [2015, 5037.5]\Omega \quad (25)$$

So we can choose any resistor of value less than 2125Ω. Let's try with $2K\Omega$ In the worst case the resistor will disipate:

$$P = (10mA)^2 \cdot 2k\Omega = 0.2W$$

So we take a resistor of $0.25W$.

$R_{LED} = 2k\Omega$	Code: RMCF1206FT2K00	Package: 1206/3216	/ 4 pt.

Q23: TL431 VOLTAGE VERIFICATION

To guarantee the correct functioning of the TL431 device, its anode-cathode voltage $V_{AK_{TL431}}$ must be greater than 2.5 V. Using the value of $i_{LED_{opto}}$ and the value of R_{LED}, and considering the typical voltage drop on the optocoupler input, compute the TL431 anode-cathode voltage in the nominal operating conditions.

ALTIUM Schematic Hints:
Connect the resistor in series to the optocoupler input. Use the designator R_{LED}.

From Q22 we have the worst case for LED voltage drop when $I_LED = 10mA$, thus:

$$V_{AK_{TL431}} = V_s - V_{octo} - I_{LED} \cdot R_{LED} = 24V - 1.35V - 10mA \cdot 2k\Omega = 2.65V \quad (26)$$

We clearly have a voltage above 2.5 V.

$V_{AK_{TL431}} = 2.65$	/ 4 pt.

Q24: TL431 BIAS RESISTOR

To guarantee the correct functioning of the TL431 device, its cathode current $i_{K,TL431}$ must be greater than 1 mA. Calculate the bias resistor considering the LED voltage drop (of around 1 V).

ALTIUM Schematic Hints:
Place the bias resistor between the positive output terminal and the TL431 cathode terminal. Use the designator R_{BIAS}.

From a LED voltage drop of around 1V, we have:

$$I_{LED} = \frac{V_{LED}}{R_{LED}} = \frac{1V}{2k\Omega} = 0.5mA \quad (27)$$

In the same way as Q23:

$$V_{AK_{TL431}} = 24 - 0.25 - 1V = 22.75V \quad (28)$$

Thus:

$$R_{bias} < \frac{V_{LED}}{I_{K,TL431}} = \frac{1V}{1mA} = 100\Omega \quad (29)$$

So we take a resistor of 75Ω.

$R_{BIAS} = 100\Omega$	Code: RMCF1206FT100R	Package: 1206/3216	/ 3 pt.

SCHEMATIC AND PCB

This section is aimed at the finalization of the ALTIUM schematic diagram and at the design of the Altium PCB.

Q25: SCHEMATIC LAYOUT

Follow the instructions given below to finalize the ALTIUM schematic diagram with the missing components.

- *Injection resistor*
  Place a 10 Ω resistor R_{INJ} between the positive terminal of the output and the R_{RH} resistor. This resistor will be used in Part 4 for the measurement of the closed-loop stability performances of the LLC converter, which is based on the injection of a small voltage perturbation. Add a jumper in parallel to the resistor R_{INJ} to allow to bypass it.

- *Test points*
  Test-Points will be used for measurement and debugging purposes. The provided Test-Point model has one connection terminal, which must be respectively connected to the desired signal and to the corresponding ground. Place Test-Points to measure the following signals:
  - input voltage, referred to the input GND;
  - output voltage, referred to the output GND;
  - the voltage on the low-side MOSFET drain terminal, referred to the input GND (square-wave middle point);
  - primary side voltage;
  - secondary side voltage;
  - the voltage on all the pins of the L6599A controller (CF, HVG, LVG), referred to the input GND;
  - the voltage on the current sensing resistor R_S, referred to the input GND;
  - the TL431 Anode-Cathode voltage and Anode-Reference voltage, referred to the output GND;
  - the zener regulated voltage, referred to the input GND.

- *Heatsinks*
  Place the heatsinks for the MOSFETs and for the Schottky Diode. Choose the correct footprint, coherently with the models chosen in Part 1. Leave their mounting connections terminals floating.

- *Decoupling capacitors*
  To improve the design against noise, place decoupling capacitors around the most sensitive pins of the controller. Refer to the L6599A controller datasheet for info.

- *Mounting holes*
  To provide mechanical stability to the circuit, place 4 mounting holes in your design, and leave them floating.

- *Redundant elements*
  For those elements which you might eventually need to tune/iterate experimentally such as resistors or capacitors, duplicate the element on your schematic and connect it in parallel, so you have another extra footprint available to solder the component in case the main footprint is damaged by the soldering/unsoldering action.

  The following components are likely to be iterated: $R_{F_{max}}$, $R_{F_{min}}$, R_A, R_B, R_S, R_G, R_{COMP_z}, C_{COMP_z}, C_{aux}, R_{LED}.

- *Resonant current measurement*
  To measure the resonant current, an external wire needs to be connected in resonant tank loop. The distance between the two endings needs to be at least 25mm, so the current probe can fit properly and hook to the wire. Add in your schematic two points between two extremes of the resonant tank to connect the wire and choose a proper footprint according the gauge of the wire. Refer to Figs.6 and 7.

Once all the previous steps have been completed, validate the schematic in ALTIUM Designer. Include here the final schematic of your LLC converter design.

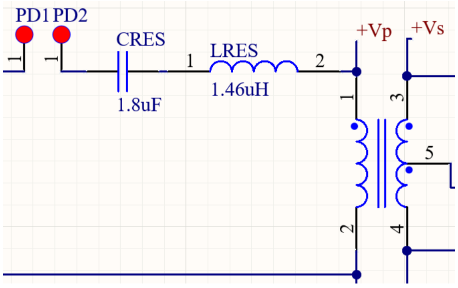

Figure 6 Measuring wire in the schematic.

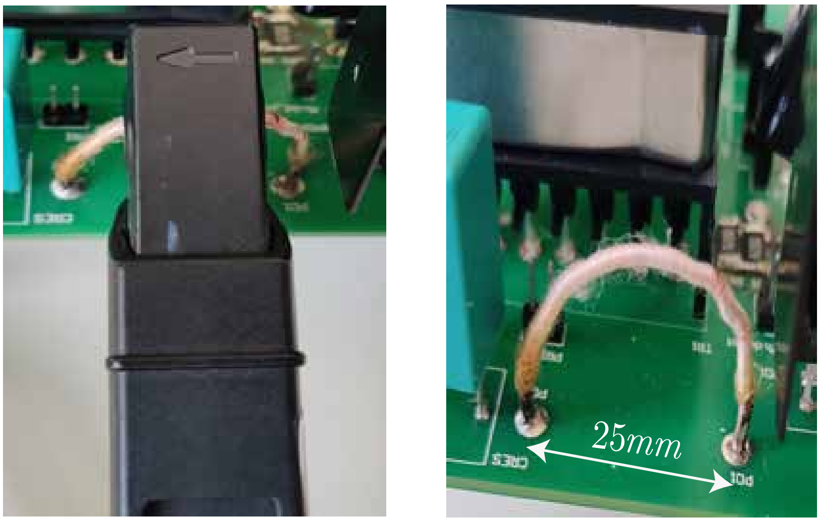

Figure 7 Measuring wire in the PCB.

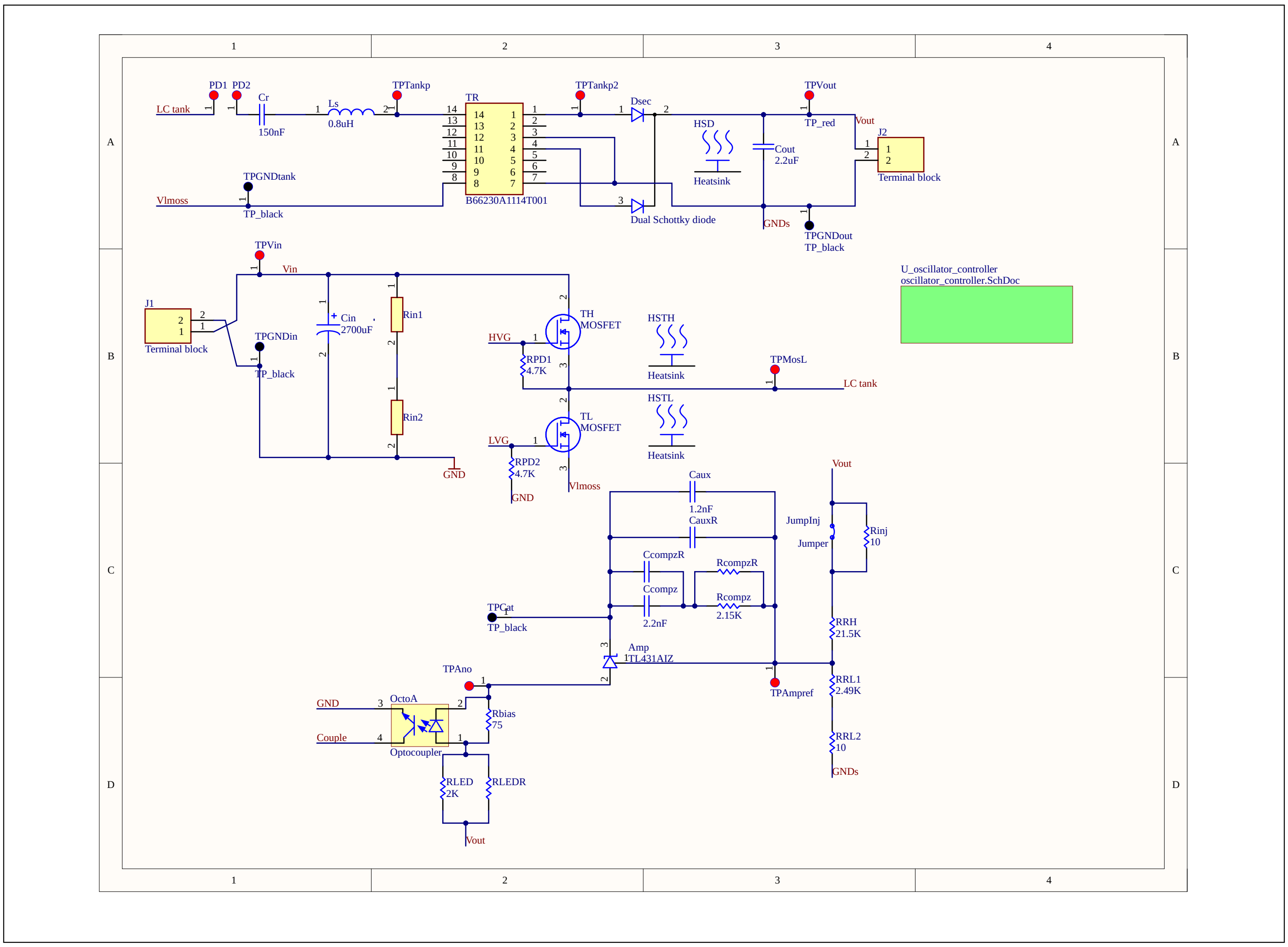

Figure 8 Power Side plus output current sensing

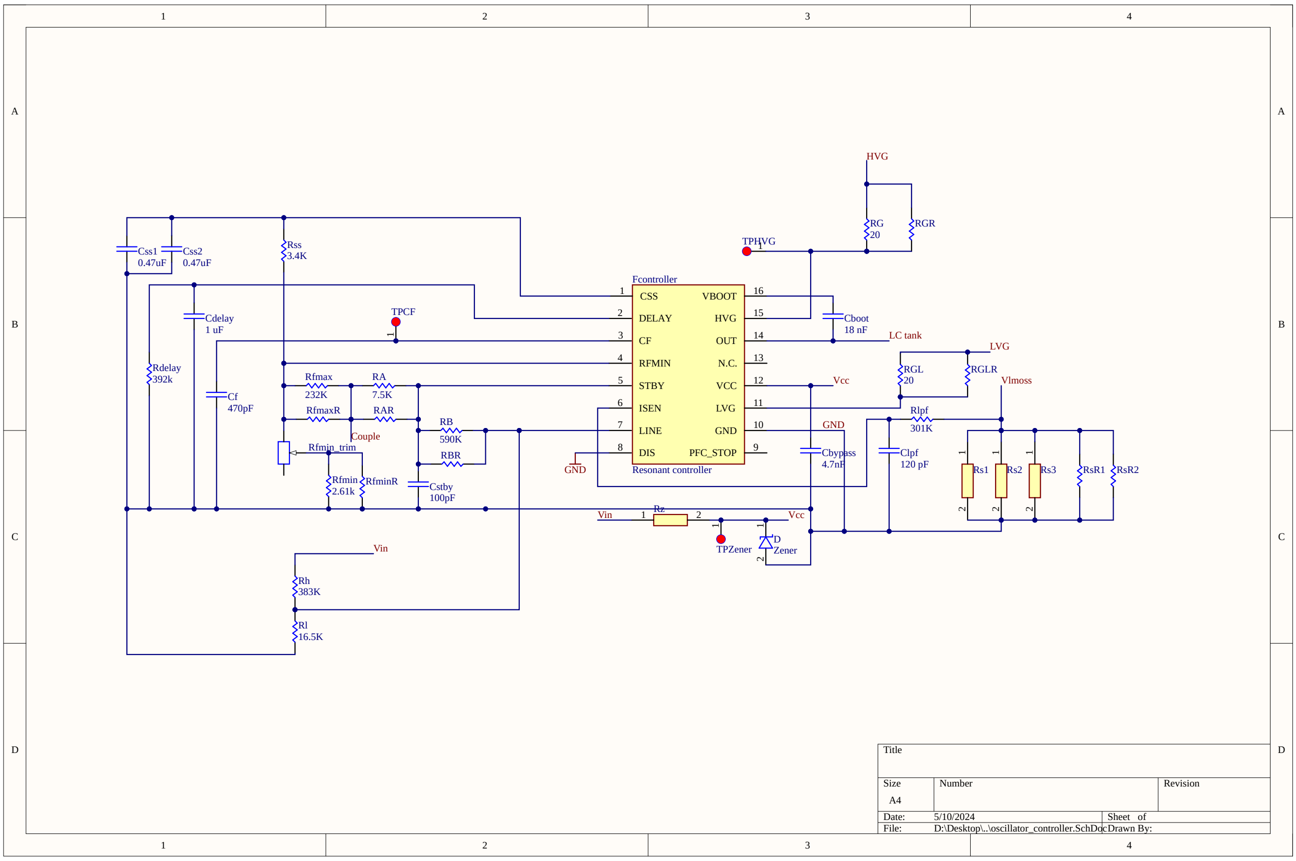

Figure 9 Resonant controller logic

/ 7 pt.

Q26: MINIMAL COPPER WIDTH FOR CURRENT-CARRYING TRACKS

Prior to routing your PCB, determine the minimal copper width needed for the current-carrying tracks. The copper thickness is fixed to 35 µm, whereas the current density is limited to $35\,\mathrm{A/mm^2}$, to limit the copper temperature rise to roughly $10\,^{\circ}\mathrm{C}$. Based on these two information and the rated current, calculate your current-carrying track width and proceed with it for power stage.

The area of the line is calculated as with k = 0.048, b = 0.44, c = 0.725 and our rated current in the worst case of I = 3.28:

$$A[mm^2] = \left(\frac{Current[Amps]}{(k * (TempRise[C])^b)}\right)^{1/c} = \left(\frac{3.28}{(0.048 * (10[C])^{0.44})}\right)^{1/0.725} = 83.87 mils^2 \quad (30)$$

Thus, also the $35\mu F = 1[oz]$:

$$d_{cu}[mils] = \frac{A}{thickness[oz] \cdot 1.378[mils/oz]} = \frac{83.87[mils^2]}{1.378[mils]} = 60.86[mils] \quad (31)$$

Also it is clear that the current density is less than the fixed one.

$d_{Cu} = 60.86 mils$

/ 5 pt.

Q27: BILL OF MATERIAL

With the help of the ALTIUM Report Manager, generate the bill of materials (BOM) needed to build your converter and include it below. This report-type document provides a list of all the required components for design realization.

In case your design requires the use of additional components not listed in the Appendix section, highlight them and be sure to provide the following information in tabular form:

- Manufacturer Part Number;
- Supplier Part Number (e.g., Digikey, Mouser, etc...);
- Supplier Link;
- Quantity (n.b., check that the needed quantity is available in stock, and that it is possible to order the exact amount needed);
- Unit Price (in CHF);
- Total Price (in CHF).

Refer, if possible, to a single supplier for all your additional required components. The Appendix provides some constraints for the additional components that can be allowed in your design.

Bill of Materials

Altium
2175 Salk Avenue
Suite 200
Carlsbad, CA 92008
USA

Project Title: Bill of Materials for BOM Document [LLC_resonant_converter.BomDoc]
Project File Name: LLC_resonant_converter.PrjPcb
Assembly Variant: None

Part Number	Description	Designator	Manufacture	Manufacture Part Number	Supplier	Supplier Part Number	Supplier Unit Price	Quantity
TL431AIZ	Automotive adjustable voltage reference	Amp	STMicroelectronics	TL431ACZ-AP	Mouser	511-TL431ACZ-AP	CHF 0.18	1
Capacitor	Non-polarized capacitor	Caux	KEMET	C1206C102J5GACTU	Mouser	80-C1206C102J5GACTU	CHF 0.19	1
Capacitor	Non-polarized capacitor	CauxR, CcompzR	KEMET	C1206C102J5GACTU	Mouser	80-C1206C102J5GACTU	CHF 0.19	2
Capacitor	Non-polarized capacitor	Cboot	KEMET	C1206C183J5RACTU	Mouser	80-C1206C183J5R	CHF 0.33	1
Capacitor	Non-polarized capacitor	Cbypass	KEMET	C1206C472J5GECTU	Mouser	80-C1206C472J5GECTU	CHF 0.38	1
Capacitor	Non-polarized capacitor	Ccompz	KEMET	C1206C222K5GEC7210	Mouser	80-C1206C222K5GECLR	CHF 0.24	1
Capacitor	Non-polarized capacitor	Cdelay	KEMET	C1206C105K3RACTU	Mouser	80-C1206C105K3R	CHF 0.17	1
Capacitor	Non-polarized capacitor	Cf	KEMET	C1206C471J5GAC	Mouser	80-C1206C471J5GAC	CHF 0.15	1
Polarized capacitor	Polarized capacitor	Cin	United Chemi-Con	EKMH630VSN272MQ35S	Mouser	661-EKMH630N272MQ35S	CHF 3.01	1
Capacitor	Non-polarized capacitor	Clpf	KEMET	C1206C121K5GACTU	Mouser	80-C1206C121K5G	CHF 0.29	1
Capacitor	Non-polarized capacitor	Cout	KEMET	C1825C225J5RACTU	Mouser	80-C1825C225J5R	CHF 3.55	1
Capacitor	Non-polarized capacitor	Cr	KEMET	C1206C154K5RACTU	Mouser	80-C1206C154K5R	CHF 0.16	1
Capacitor	Non-polarized capacitor	Css1, Css2	KEMET	C1206C474K3RACTU	Mouser	80-C1206C474K3R	CHF 0.19	2
Capacitor	Non-polarized capacitor	Cstby	KEMET	C1206C101J1GAC7210	Mouser	80-C1206C101J1GACLR	CHF 0.15	1
Zener	Zener diode	D	ON Semiconductor / Fairchild	1N5245BTR	Mouser	512-1N5245BTR	CHF 0.14	1
Dual Schottky diod	Dual Schottky diode	Dsec	ROHM Semiconductor	RB085T-90NZC9	Mouser	755-RB085T-90NZC9	CHF 1.18	1
Resonant controlle	L6599A resonant controller	Fcontroller	STMicroelectronics	L6599AN	Mouser	511-L6599AN		1
Heatsink	General purpose heatsink	HSD, HSTH, HSTL	Ohmite	E2A-T220-25E	Mouser	588-E2A-T220-25E	CHF 1.80	3
Terminal block	Two pins terminal block	J1, J2						2
Jumper	Two pin jumper	JumpInj						1
Inductor	Inductor	Ls						1
Optocoupler	General purpose optocoupler	Octo	Vishay Semiconductors	VO617A-3X016	Mouser	78-VO617A-3X016	CHF 0.21	1
TP_red	Test point	PD1, PD2, TPAmpref, TPAno, TPCF, TPHVG, TPMosL, TPTankp, TPTankp2, TPVin, TPVout, TPZener						12
Resistor	Resistor	RA	Stackpole Electronics	RMCF1206FT7K50	Mouser	708-RMCF1206FT7K50	CHF 0.09	1
Resistor	Resistor	RAR, RBR, RcompzR, RfmaxR, RfminR, RGLR, RGR, RLEDR, RsR1, RsR2	SEI	RMCF1206FT1K00	Avnet, Arrow Electronics, Digikey	RMCF1206FT1K00, RMCF1206FT100K, RMCF1206FT21K5, RMCF1206FT232K, 738-RMCF1206FT2K61CT-ND, RMCF1206FT20R0, SR2512FK-7W2KL		10
Resistor	Resistor	RB	Stackpole Electronics	RMCF1206FT590K	Mouser	708-RMCF1206FT590K	CHF 0.01	1
Resistor	Resistor	Rbias	Stackpole Electronics	RMCF1206FT75R0	Mouser	708-RMCF1206FT75R0	CHF 0.09	1
Resistor	Resistor	Rcompz	Stackpole Electronics	RMCF1206FT2K15	Mouser	708-RMCF1206FT2K15	CHF 0.09	1
Resistor	Resistor	Rdelay	Stackpole Electronics	RMCF1206FT392K	Mouser	708-RMCF1206FT392K	CHF 0.01	1
Resistor	Resistor	Rfmax	Stackpole Electronics	RMCF1206FT232K	Mouser	708-RMCF1206FT232K	CHF 0.01	1
Resistor	Resistor	Rfmin	Stackpole Electronics	RMCF1206FT2K61	Mouser	708-RMCF1206FT2K61	CHF 0.01	1
Variable Resistor	Variable Resistor	Rfmin_trim	Nidec Copal	CT-6EP102	Mouser	229-CT-6EP102	CHF 1.15	1
Resistor	Resistor	RG, RGL	Stackpole Electronics	RMCF1206FT20R0	Mouser	708-RMCF1206FT20R0	CHF 0.10	2
Resistor	Resistor	Rh	Stackpole Electronics	RMCF1206FT383K	Mouser	708-RMCF1206FT383K	CHF 0.01	1
CRGP2512F3K3	Resistor	Rin1, Rin2	TE Connectivity	CRGP2512F3K3	Mouser	279-CRGP2512F3K3	CHF 0.54	2
Resistor	Resistor	Rinj, RRL2	SEI	RMCF1206FT10R0	Mouser	708-RMCF1206FT10R0	CHF 0.09	2
Resistor	Resistor	Rl	Stackpole Electronics	RMCF1206FT16K5	Mouser	708-RMCF1206FT16K5	CHF 0.01	1
Resistor	Resistor	RLED	Yageo	SR2512FK-7W2KL	Mouser	603-SR2512FK-7W2KL	CHF 0.93	1
Resistor	Resistor	Rlpf	Stackpole Electronics	RMCF1206FT301K	Mouser	708-RMCF1206FT301K	CHF 0.01	1
Resistor	Resistor	RPD1, RPD2	Stackpole Electronics	RMCF1206FT4K70	Mouser	708-RMCF1206FT4K70	CHF 0.09	2
Resistor	Resistor	RRH	Stackpole Electronics	RMCF1206FT21K5	Mouser	708-RMCF1206FT21K5	CHF 0.01	1
Resistor	Resistor	RRL1	Stackpole Electronics	RMCF1206FT2K49	Mouser	708-RMCF1206FT2K49	CHF 0.90	1
3430H2F1R2TDF	Resistor	Rs1, Rs2, Rs3	3430H2F1R2TDF	3430H2F1R2TDF	Mouser	279-3430H2F1R2TDF	CHF 0.54	3
Resistor	Resistor	Rss	Stackpole Electronics	RMCF1206FT3K40	Mouser	708-RMCF1206FT3K40	CHF 0.01	1
SR2512JK-7W1KL	Resistor	Rz	Yageo	SR2512JK-7W1KL	Mouser	603-SR2512JK-7W1KL	CHF 0.52	1
MOSFET	MOSFET (N-Channel)	TH, TL	ON Semiconductor / Fairchild	FDPF680N10T	Mouser	512-FDPF680N10T	CHF 1.41	2
TP_black	Test point	TPCat, TPGNDin, TPGNDout, TPGNDtank	Inhouse	1				4
B66230A1114T001	Inductor	TR	TDK EPCOS	B66230A1114T001	Mouser	871-B66230A1114T001	CHF 2.07	1
							CHF 21.20	83

Approved	Notes

Figure 10 Bill of Material LLC converter PCB

List of components				
Mouser part number	Mouser description	Quantity	Unit price	Link
80-C1825C225J5R	Condensateurs céramique multicouches MLCC - CMS 50V 2.2uF X7R 1825 5%	1	CHF 3.56	https://www.mouser.ch/ProductDetail/KEMET/C1825C225J5RACTU?qs=GduLp7PHHqRkbaNlFXCaVw%3D%3D
279-CRGP2512F3K3	Résistances à couches épaisses - CMS CRGP 2512 3K3 1% SMD Resistor	3	CHF 0.54	https://www.mouser.ch/ProductDetail/TE-Connectivity-Holsworthy/CRGP2512F3K3?qs=wUXugUrL1qxk6tnc3bkPuQ%3D%3D
279-3430H2F1R2TDF	Résistances à couches épaisses - CMS 3430 H2 1% 1R2 150ppm 1k RL	4	CHF 0.54	https://www.mouser.ch/ProductDetail/TE-Connectivity-Holsworthy/3430H2F1R2TDF?qs=8Wlm6%252BaMh8QfdfpWQrhwpg%3D%3D
229-CT-6EP102	Trimmer Resistors - Through Hole 1 KW 6mm sq. single turn top adj, std type	2	CHF 1.15	https://www.mouser.ch/ProductDetail/Nidec-Components/CT-6EP102?qs=XeJtXLiO41Q%252BHWRCeXOcUQ%3D%3D
		Total	CHF 15.79	

Figure 11 Extra components

/ 4 pt.

Q28: PCB LAYOUT

Before manufacturing the PCB of the designed converter, it is necessary to check that the connections and component placings were done correctly. For this purpose, route your PCB, following the guidelines given below.

For this course, the PCB prototype is limited to **two layers**. It is not allowed to exceed the maximum size set by the provided template.

For best performances, partition the PCB by physically grouping components:
- Power circuitry (MOSFETs, diodes, transformer, resonant tank, input and output capacitors, input and output terminals, etc...);
- Control circuitry (L6599A controller, Optocoupler, TL431, etc...).

Set a minimum insulation distance of 0.2 mm (8 mils) between the PCB traces.

Use a minimum width of 0.5 mm (20 mils) for the signal tracks. Respect the minimum width computed in Q26 for the power tracks. Consider using a primary-side GND plane and a secondary-side GND plane, and be sure to keep them isolated from one another.

Auto-routing is not allowed. Route in the following order:
- Power stage (Input capacitor, MOSFETs, diode, transformer...) to have the minimum physical loop on the board, as this loop will be the source of interference.
- Auxiliary measurement and control circuits.

You can use vias to connect tracks on the two sides of the PCB. Avoid using vias in main current path, or use bigger vias, or vias in parallel to increase current carrying capability (in such a case, the inner diameter must be higher than vias used for signal paths).

For almost all the components you need, you will find the footprints in the provided Altium template. However, for some other elements such as discharge resistors, shunt resistors or any resistor that could dissipate a considerable amount of power, the use wider pads to offer thermal relief to the device package is strongly recommended. This could help to avoid overheating in these resistors.

Place the mounting holes in the opposite sides of the board, in a way to ensure a good mechanical stability.
Verify that the heatsinks are properly aligned to the MOSFET and Schottky Diode.

For some components, such as the transformer and resonance capacitor, you will need to select a specific footprint for the selected component. You can either download one or design your own. In most cases you will find some websites where you can download all the footprints you need, so designing each component is not necessary in most cases. We strongly recommend that you install this extension which can provide you with many footprints: *SamacSys extension.*. You can also find many footprints in *SnapMagic*.

Annotate the PCB silkscreen with all the required information (e.g., connector polarities, components identifiers, etc...).

Run a design rule check in ALTIUM Designer, and correct all the errors.

Include below a 2D and 3D view of the top and bottom layers of your final PCB layout.

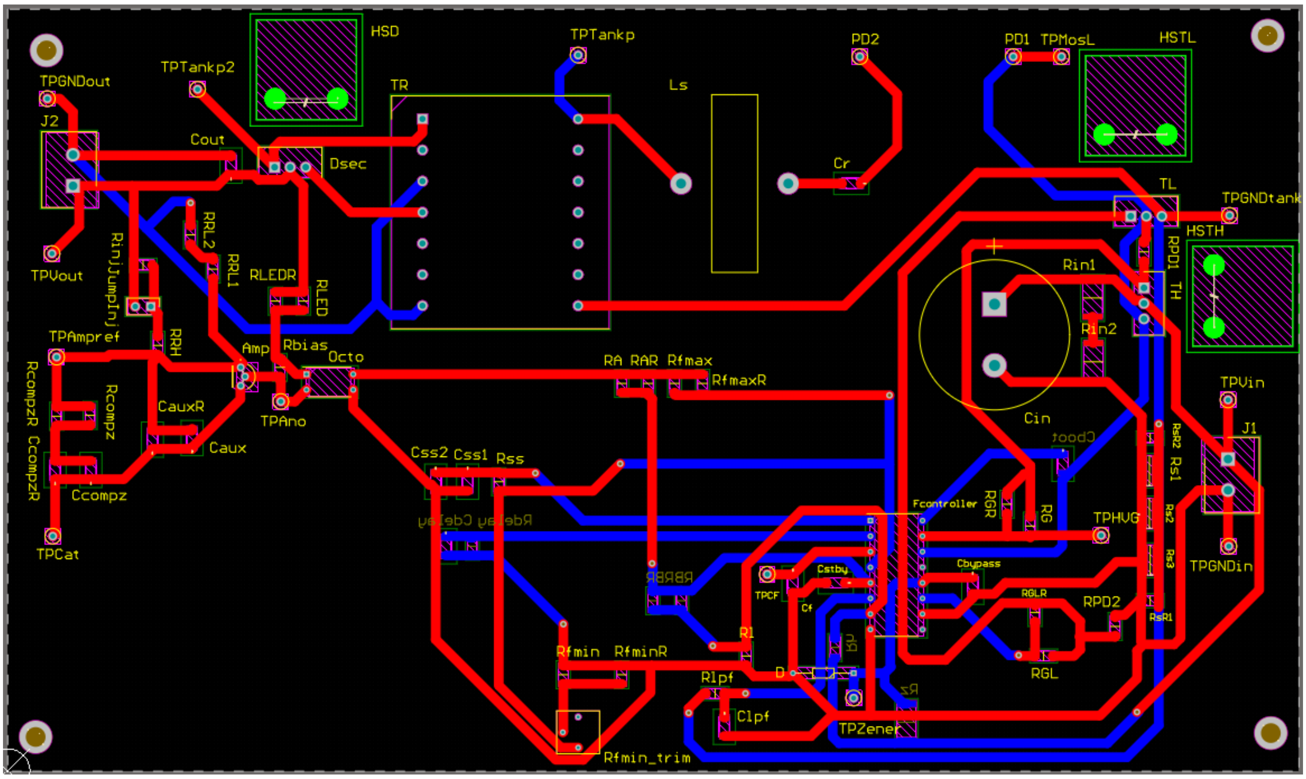

Figure 12 PCB top view in 2D mode.

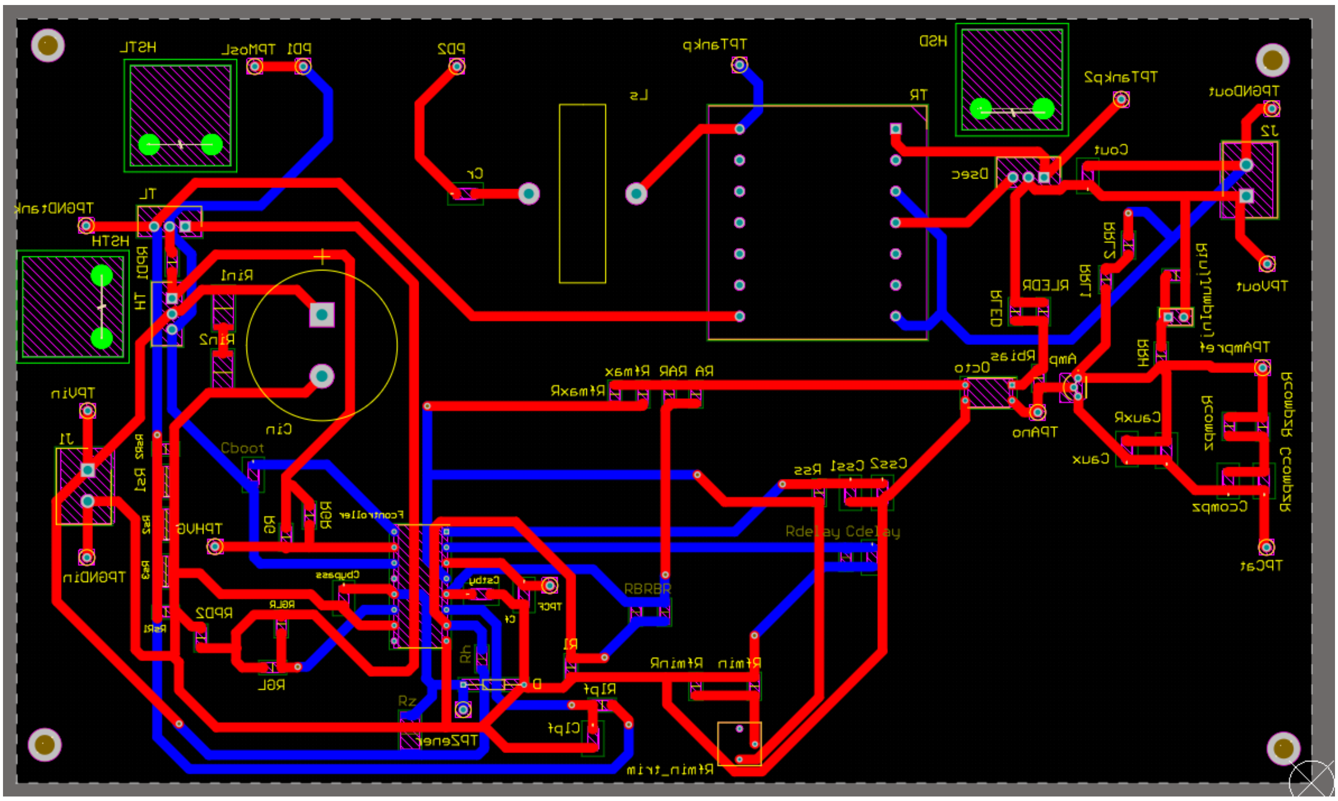
Figure 13 PCB bottom view in 2D mode.

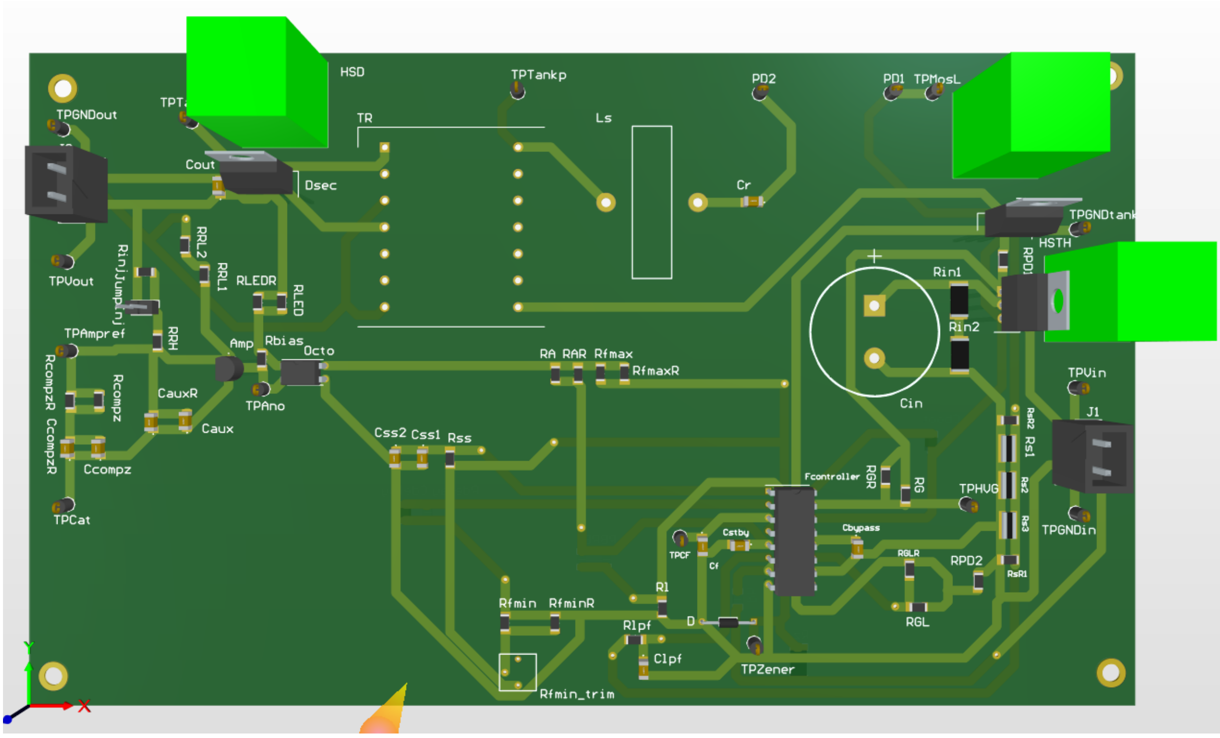

Figure 14 PCB top view in 3D mode.

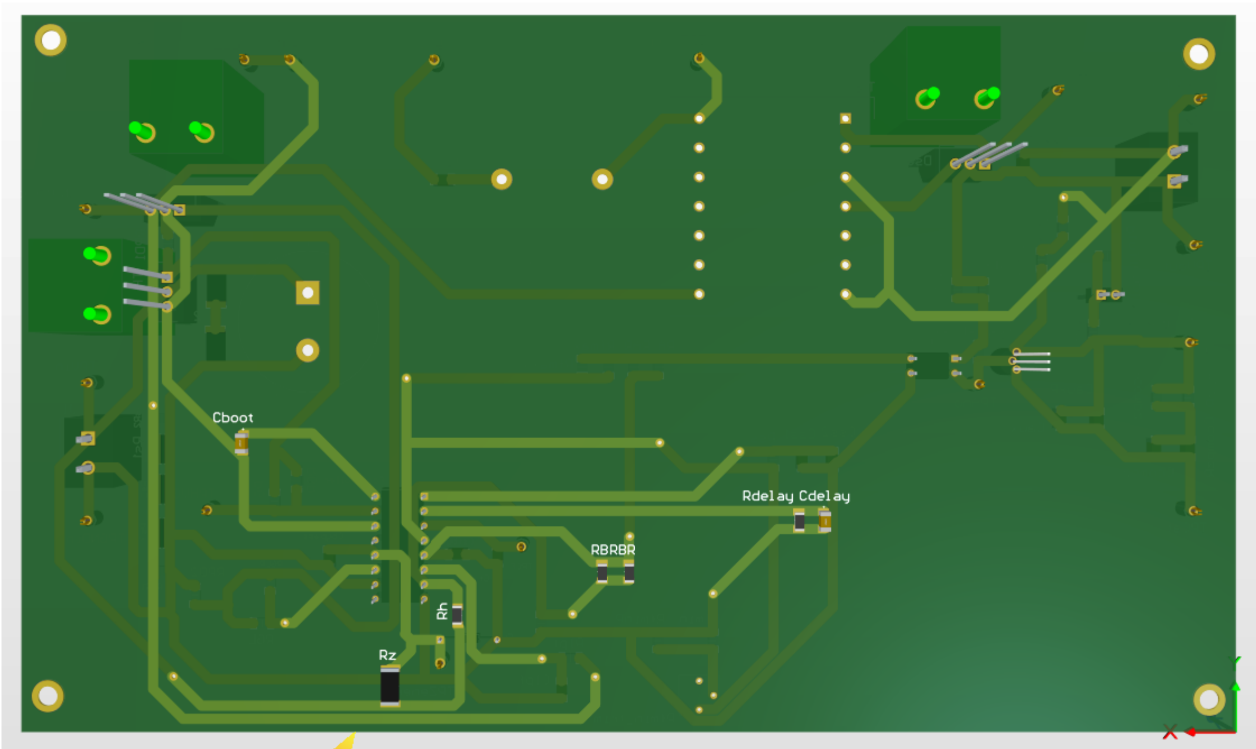

Figure 15 PCB bottom view in 3D mode.

/ 7 pt.

APPENDIX

This section contains the list of available components that can be used in your design, and some specification requirements for additional components.

LIST OF AVAILABLE SMD CAPACITORS

The list of available SMD Ceramic Capacitors is given in Table 2. Refer to these values for your design.
For information about the power ratings of different SMD ceramic capacitors, refer to Table 1.

Table 1 Power ratings of different SMD ceramic capacitors packages, empirically determined considering a temperature rise of 25 °C rise above the ambient temperature (Source: Johanson Dielectrics).

Package (Imperial/Metric)	1206/3216	1210/3225	1812/4532	2512/6332
Power Rating	80 mW	200 mW	400 mW	900 mW

Table 2 List of available SMD Ceramic Capacitors

Manufacturer	Part Number	Package (Imperial/Metric)	Capacitance		Tolerance (%)	Rated Voltage (V)
KEMET	C1206C100J2GACTU	1206/3216	10	pF	±5	200
KEMET	C1206C220F2GACTU	1206/3216	22	pF	±1	200
KEMET	C1206C330F2GACTU	1206/3216	33	pF	±1	200
KEMET	C1206C470F2GACTU	1206/3216	47	pF	±1	200
KEMET	C1206C101J1GACTU	1206/3216	100	pF	±5	100
KEMET	C1206C221J1GACTU	1206/3216	220	pF	±5	100
KEMET	C1206C471J1GACTU	1206/3216	470	pF	±5	100
KEMET	C1206C102J1GACTU	1206/3216	1000	pF	±5	100
KEMET	C1206C222K1GACTU	1206/3216	2200	pF	±10	100
KEMET	C1206C472K5GACTU	1206/3216	4700	pF	±10	50
KEMET	C1206C222K2RACTU	1206/3216	2200	pF	±10	200
KEMET	C1206C104K5RACTU	1206/3216	0.1	μF	±10	50
KEMET	C1206C154K5RACTU	1206/3216	0.15	μF	±10	50
KEMET	C1206C224K5RACTU	1206/3216	0.22	μF	±10	50
KEMET	C1206C334K5RACTU	1206/3216	0.33	μF	±10	50
KEMET	C1206C474K3RACTU	1206/3216	0.47	μF	±10	25
KEMET	C1206C105K3RACTU	1206/3216	1	μF	±10	25
KEMET	C1206C225K5RACTU	1206/3216	2.2	μF	±10	50
KEMET	C1206C106K4RACTU	1206/3216	10	μF	±10	16
KEMET	C1206C225K4PACTU	1206/3216	2.2	μF	±10	16
KEMET	C1206C335K3PACTU	1206/3216	3.3	μF	±10	25
KEMET	C1206C475K3PACTU	1206/3216	4.7	μF	±10	25
KEMET	C1206C106K4PACTU	1206/3216	10	μF	±10	16
KEMET	C1206C153K5RAC7800	1206/3216	15	nF	±10	50
KEMET	C1206S103J5RACAUTO	1206/3216	10	nF	±5	50
YAGEO	CC1206KRX7RYBB472	1206/3216	4.7	nF	±10	250
Samsung EM	CL31B102KDCNNNC	1206/3216	1.0	nF	±10	200
Würth El.	885342208003	1206/3216	10	nF	±10	250

Manufacturer	Part Number	Package (Imperial/Metric)	Capacitance		Tolerance (%)	Rated Voltage (V)
KEMET	C1206C100J1GAC	1206/3216	10	pF	±5	100
KEMET	C1206C120J5GACTU	1206/3216	12	pF	±5	50
KEMET	C1206C150J5GAC7800	1206/3216	15	pF	±5	50
KEMET	C1206C180J5GAC	1206/3216	18	pF	±5	50
KEMET	C1206C220J5GAC7800	1206/3216	22	pF	±5	50
KEMET	C1206C270J5GACTU	1206/3216	27	pF	±5	50
KEMET	C1206C330J5GAC7800	1206/3216	33	pF	±5	50
KEMET	C1206C390J5GACTU	1206/3216	39	pF	±5	50
KEMET	C1206C470J5GAC7800	1206/3216	47	pF	±5	50
KEMET	C1206C560J5GACTU	1206/3216	56	pF	±5	50
KEMET	C1206C680K5GACTU	1206/3216	68	pF	±10	50
KEMET	C1206C820J1GACTU	1206/3216	82	pF	±5	100
KEMET	C1206C101J1GAC7210	1206/3216	100	pF	±5	100
KEMET	C1206C121K5GACTU	1206/3216	120	pF	±10	50
KEMET	C1206C151J5GAC7800	1206/3216	150	pF	±5	50
KEMET	C1206C181J5GACTU	1206/3216	180	pF	±5	50
KEMET	C1206C221J5GACTU	1206/3216	220	pF	±5	50
KEMET	C1206C271K5GACTU	1206/3216	270	pF	±10	50
KEMET	C1206C331J5GAC7800	1206/3216	330	pF	±5	50
KEMET	C1206C391J5GACTU	1206/3216	390	pF	±5	50
KEMET	C1206C471J5GAC	1206/3216	470	pF	±5	50
KEMET	C1206C561J5GACTU	1206/3216	560	pF	±5	50
KEMET	C1206C681J5GACTU	1206/3216	680	pF	±5	50
KEMET	C1206C821J5GAC7800	1206/3216	820	pF	±5	50
KEMET	C1206C102J5GAC7800	1206/3216	1	nF	±5	50
KEMET	C1206C122J1GACTU	1206/3216	1.2	nF	±5	100
KEMET	C1206C152K5GACTU	1206/3216	1.5	nF	±10	50
KEMET	C1206C182J5GACTU	1206/3216	1.8	nF	±5	50
KEMET	C1206C222K5GEC7210	1206/3216	2.2	nF	±10	50
KEMET	C1206C272J5GACTU	1206/3216	2.7	nF	±5	50
KEMET	C1206C332J5GACTU	1206/3216	3.3	nF	±5	50
KEMET	C1206C392JAGACAUTO	1206/3216	3.9	nF	±5	250
KEMET	C1206C472J5GECTU	1206/3216	4.7	nF	±5	50
KEMET	C1206C562JCGACAUTO	1206/3216	5.6	nF	±5	500
KEMET	C1206C682JCGACAUTO	1206/3216	6.8	nF	±5	500
KEMET	C1206C822JBGACTU	1206/3216	8.2	nF	±5	630
KEMET	C1206S103J5RACAUTO	1206/3216	10	nF	±5	50
KEMET	C1206C123J5RACTU	1206/3216	12	nF	±5	50
KEMET	C1206C153J5RACTU	1206/3216	15	nF	±5	50
KEMET	C1206C183J5RACTU	1206/3216	18	nF	±5	50
KEMET	C1206C223J5RACAUTO	1206/3216	22	nF	±5	50
KEMET	C1206C273J5RACTU	1206/3216	27	nF	±5	50
KEMET	C1206C333J2RECTU	1206/3216	33	nF	±5	200
KEMET	C1206C393JARACTU	1206/3216	39	nF	±5	250
KEMET	C1206X473JARECTU	1206/3216	47	nF	±5	250
KEMET	C1206C473J1RECAUTO	1206/3216	47	nF	±5	100
KEMET	C1206C563K5RACTU	1206/3216	56	nF	±10	50
KEMET	C1206C683J1RECAUTO	1206/3216	68	nF	±5	100
KEMET	C1206C823J5RACTU	1206/3216	82	nF	±5	50

LIST OF AVAILABLE SMD RESISTORS

The SMD Resistors can be chosen from Table 3. This table includes both SMD resistor kits and individual resistor values.
For the resistance codes of the Stackpole Electronics Kits it is possible to refer to Fig.16.

Table 3 List of available SMD Resistors (Individual and Kits).

Manufacturer	Part Number	Package (Imperial/Metric)	Resistance Value(s) (Single or Kit)	Tolerance (%)	Rated Power (W)
Stackpole Electronics	KIT-RMCF1206FT-02	1206/3216	E96 values from 10 Ω to 97.6 Ω	±1	0.25
Stackpole Electronics	KIT-RMCF1206FT-03	1206/3216	E96 values from 100 Ω to 976 Ω	±1	0.25
Stackpole Electronics	KIT-RMCF1206FT-04	1206/3216	E96 values from 1 kΩ to 9.76 kΩ	±1	0.25
Stackpole Electronics	KIT-RMCF1206FT-05	1206/3216	E96 values from 10 kΩ to 97.6 kΩ	±1	0.25
Stackpole Electronics	KIT-RMCF1206FT-06	1206/3216	E96 values from 100 kΩ to 976 kΩ	±1	0.25
Stackpole Electronics	KIT-RMCF1206JT-14	1206/3216	E96 values from 100 kΩ to 10 MΩ	±5	0.25
Stackpole Electronics	RMCF1206FT10R0	1206/3216	10 Ω	±1	0.25
Vishay Dale	CRCW120620R0FKEA	1206/3216	20 Ω	±1	0.25
YAGEO	SR2512JK-7W1KL	2512/6332	1 kΩ	±5	2
YAGEO	SR2512FK-7W2KL	2512/6332	2 kΩ	±1	2
TE Connectivity	CRGP2512F3K3	2512/6332	3.3 kΩ	±1	2
TE Connectivity	CRGP2512F10K	2512/6332	10 kΩ	±1	2
Stackpole Electronics	CSM2512FT50L0	2512/6332	50 mΩ	±1	2
Stackpole Electronics	CSRN2512FKR100	2512/6332	100 mΩ	±1	2
Stackpole Electronics	CSRN2512FKR150	2512/6332	150 mΩ	±1	2
Stackpole Electronics	CSRN2512FKR200	2512/6332	200 mΩ	±1	2

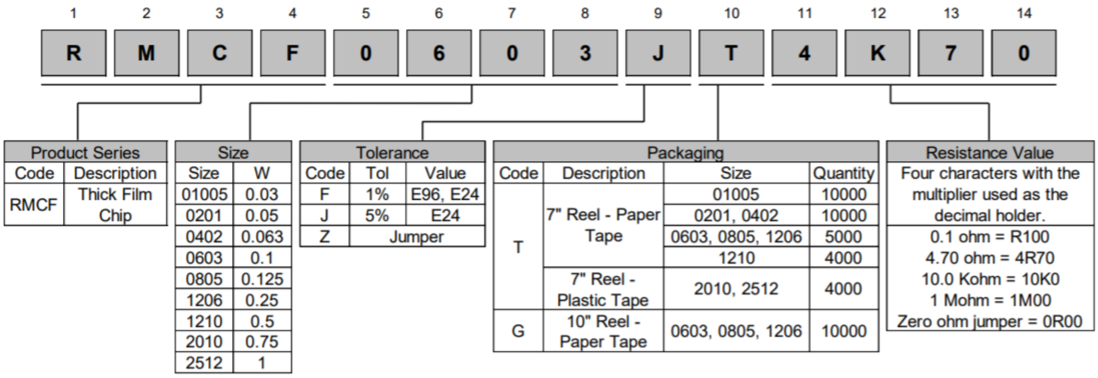

Figure 16 Resistor Code for Stackpole Electronics Kits.

LIST OF AVAILABLE TRIMMERS

The trimmers can be chosen from Table 4. They can be used in combination with the R_{RT} resistor and with the R_{FBU} resistor to allow for some small adjustments.

All trimmers are Through-hole and have the same footprint.
Be sure to connect the correct terminals when using the trimmers in your design.

Table 4 List of available zener diodes.

Manufacturer	Part Number	Nominal Resistance	Tolerance (%)	Rated Power (W)
Nidec Copal Electronics	CT6EP102	1 kΩ	±10	0.5
Nidec Copal Electronics	CT6EP502	5 kΩ	±10	0.5

LIST OF AVAILABLE ZENER DIODES

The zener diodes can be chosen from Table 5. You can choose the ones that fit your requirements the best or the ones that you find the most suitable for your design.

Be aware that different zener diodes can have different footprints.
Be sure to connect the correct terminals when using the zener diode in your design.

Table 5 List of available zener diodes.

Manufacturer	Part Number	Zener voltage	Tolerance (%)	Rated Power (W)
Onsemi	1N5245BTR	15V	±5	0.5
Vishay	BZX55B12-TAP	12 V	±2	0.5
NEXPERIA	1N4742A,113	12 V	±5	1

RULES FOR ADDITIONAL COMPONENTS

The use of additional components not listed in the appendix is allowed, but it needs to be properly motivated and authorized.

Only the following components can be authorized:
- Input and Output capacitors;
- Diodes (auxiliary circuit and Zener diodes);
- Auxiliary circuit Limiting Resistor;
- Gate Resistor.

Note also that:
- Additional **SMD** components are limited to the package **1206 or bigger**;
- All **diodes** are limited only to **through-hole** technology.

To this purpose, the group is asked to provide in Q27 the following information in tabular form:
- Manufacturer Part Number;
- Supplier Part Number (e.g., Mouser, Digikey, etc...);
- Supplier Link;
- Quantity (n.b., check that the needed quantity is available in stock, and that it is possible to order the exact amount needed);
- Unit Price (in CHF);
- Total Price (in CHF).

Refer, if possible, to a single supplier for all your additional required components.