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Title

R4: LLC RESONANT CONVERTER - ASSEMBLING AND TESTING

Course Name

EE-365 Power Electronics

Keywords

Assembling, Testing

TABLE OF CONTENTS

OVERVIEW

The last part of the project course deals with the assembling and testing of the designed LLC resonant converter.

To facilitate the debugging, assembling, and testing they are here divided into different steps, aimed at individually verifying the correct behavior of each part of the converter.

During the testing, the following instrumentation will be used:

- *Elektro-Automatik EA-PSI 5200-10A* DC power supplies (or equivalent power supplies),
- *BK Precision 8542B* Active Load,
- *Rigol DS1074Z* Oscilloscope,
- *Newtons4th Ltd PPA5530* Power Analyzer,
- *Omicron Lab Bode 100* Multifunctional Test Set,
- *FLIR E60* Thermal Camera.

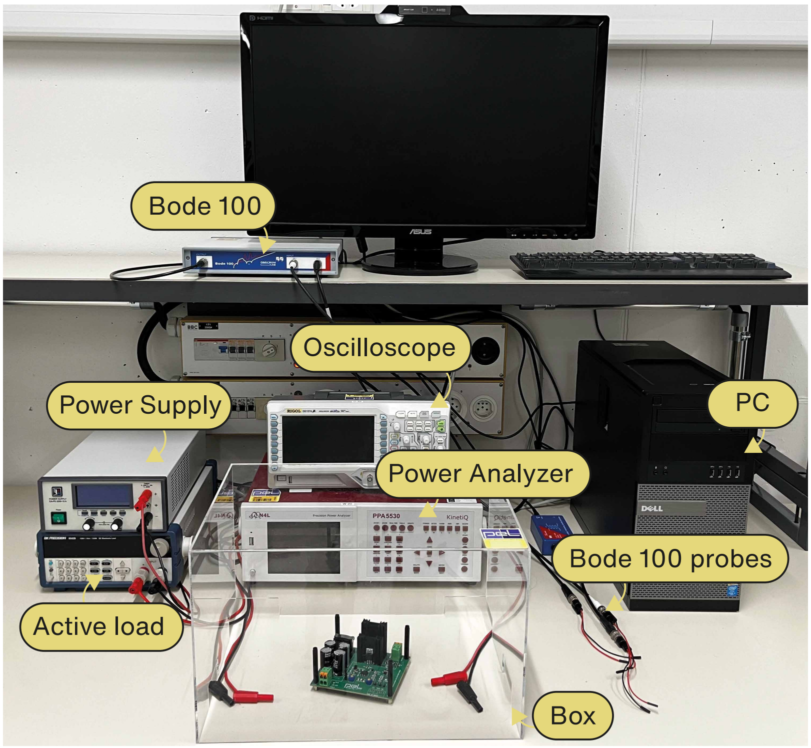


Figure 1 Complete test setup

SUGGESTION OF REPORT STYLE

Give a full explanation of how you have carried out the tests. Provide an explanation if major modifications to the PCB are required. If you cannot proceed with testing, provide evidence of the test setup you would use and explain what mistake is preventing you from proceeding and how you could improve your design if a second design iteration was allowed.
You are requested to save your oscilloscope acquisition on a USB stick to ensure proper visualization of the results.

SOLDERING TECHNOLOGY

You are free to choose the soldering method, you can use our laboratory facilities or also external facilities. Be aware that certain tests need to be performed without some components soldered. Every time, after you solder a component, check the continuity with a multimeter and look for unintentional short circuits.

VOLTAGE PROBES USAGE

In some questions, you will be asked to perform some voltage grounded or isolated measurements. A grounded measurement, as the name suggests, is a measurement made between a given point and the reference (ground). On the other hand, an isolated measurement is made between two points that are floating, i.e. neither of them is connected to ground. The figure below shows an example of a grounded and floating measurement.
For grounded measurements, you can use low voltage grounded probes. However, for isolated measurements, it is important that

you use the differential probes. Ground connector of non isolated probes is connected to the oscilloscope ground. When performing simultaneous grounded measurements which are referred to different grounds (e.g. primary and secondary) use at least one isolated probe, do not connect the two grounds through the oscilloscope.
Be careful when connecting the probes to the test points, as there could be some components surrounding the test points that could lead to a short circuit if they are touched by the ground connector of the probe. Connect the probes in a stable manner before energizing the converter and do not move them until you power it off.
When measuring, always verify the attenuation factor of the probe.

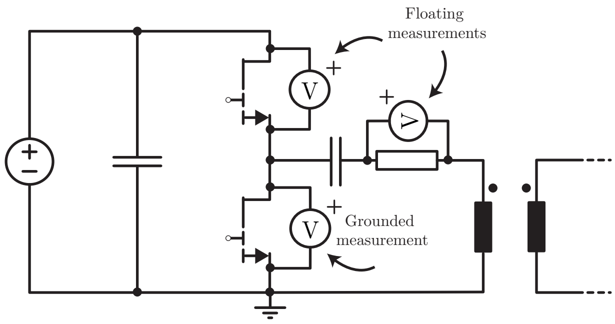


Figure 2 Example of a grounded and floating measurements.

SOLDERING OF VARIABLE RESISTORS

If you included Through-Hole variable resistors (i.e., Trimmers) in your design, follow this approach. Before soldering, measure with a multimeter what is the actual resistance between the terminals, and adjust it to be close to the rated value of the design.

PRELIMINARY ASSEMBLING AND TESTING

SOLDERING OF CONNECTORS, SOCKETS, JUMPERS, AND TEST POINTS

Solder the input and output power connectors, the socket of the L6599a device, the socket of the optocoupler, the jumpers, and all the test points.

Q1: INPUT CAPACITOR VOLTAGE WITHSTANDING AND DISCHARGE TIME VERIFICATION

Solder the input capacitor and the discharging resistor (R_{in}). Use the power supply to provide your maximum input voltage to the converter input terminals. Be careful to respect the correct polarity of the capacitor and the power supply.

Measure the input voltage with the voltage probe (between the input capacitor terminals) and then set the trigger mode of the oscilloscope. Then proceed to set the power supply output to "OFF". The oscilloscope should now capture the transient response of the capacitor's voltage and you should be able to observe the voltage discharge curve. Measure the discharge time of the input voltage until approximately 5 % of the initial value. Compare the results with the design choice in Report 3 and comment on the results.

From Report 3, we have:

$$T_{disch} = -R_{in} \cdot C_{in} \cdot ln(0.05) = -5k\Omega \cdot 2700\mu F \cdot ln(0.05) = 40.44s$$

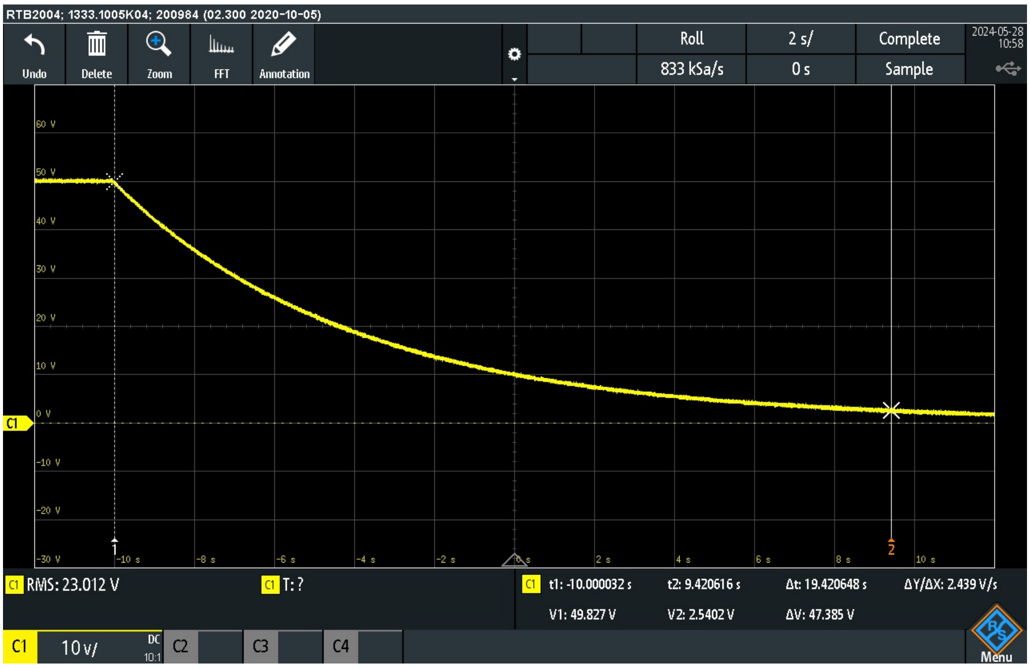


Figure 3 Oscilloscope capture of the discharge time

$\Delta T_{Cin,disch,theory} = 40.4s$	$\Delta T_{Cin,disch,meas} = 19.4s$	/ 5 pt.

Q2: ZENER DIODE AND IC VOLTAGE SUPPLY

Continue by soldering the zener diode network (zener diode and R_z). Take into account the polarity of the zener diode when you solder it. To do this, you can use a multimeter in diode mode to identify the polarity by forward biasing the diode and measuring the voltage drop. The cathode is usually identified by a line drawn inside the component.

As explained in report 2, the zener network must provide a constant regulated output voltage (measured between cathode (+) and anode (-)) of 15V, which is the designated supply voltage of the IC L6599a. This regulation must be guaranteed in the given range (from $V_{in} = 30\ V$ to $V_{in} = 50\ V$), that is, the regulated voltage should be constant for the whole range. Some variations are expected because of the zener voltage tolerance. Make sure that this variation does not bring the regulated voltage above the maximum allowable supply voltage of the IC controller.

For this measurement, without the IC plugged in the socket, connect the input power supply to the input connector. With the non-isolated oscilloscope probe, measure the zener voltage (between VCC pin and primary-side GND, by properly connecting to the corresponding test points) and verify if the zener diode is clamping the voltage as expected in the whole input voltage range (from $V_{in} = 30\ V$ to $V_{in} = 50\ V$). Be careful to respect the correct polarity.

Export the waveforms of the oscilloscope for both measurements of the V_{cc} pin, at $V_{in} = 30\ V$ and $V_{in} = 50\ V$.

Comment on the behavior of the Zener diode network for input voltages lower than 30 V.

<u>Hints:</u>
Set the power supply to have an OCP (Over Current Protection) of 1 A.

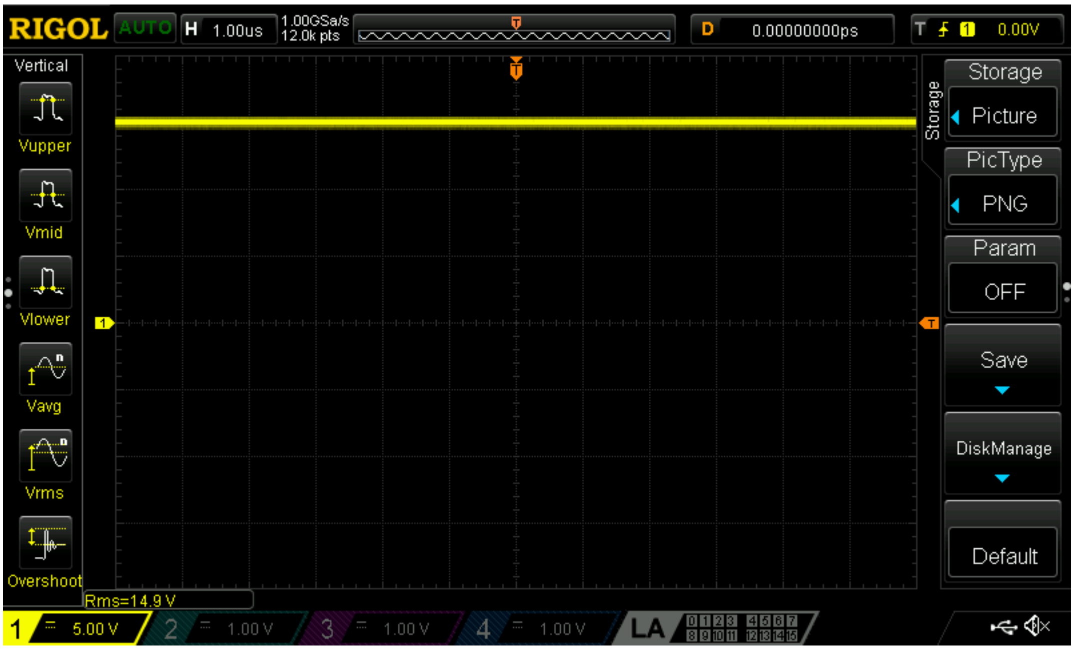


Figure 4 Zener Diode Voltage at $V_{CC,@30}$

Figure 5 Zener Diode Voltage at $V_{CC,@50}$

$V_{CC,@30}$ = 14.9 | $V_{CC,@50}$ = 15.2 | / 6 pt.

VERIFICATION OF THE CORRECT FUNCTIONALITY OF IC L6599A

Q3: VERIFICATION OF THE OSCILLATOR PIN

Solder the IC network resistors and capacitors, including the sensing resistors and plug the IC in the socket. Continue by soldering the external gate resistors and the pull-down resistor in each gate-to-source terminal of each MOSFET.

Using the oscilloscope, measure the switching frequency of the signal at the CF pin (use the test point) of the IC and comment on the results.

Export the waveforms of the oscilloscope and provide the measured switching frequency you obtained.

Hints:
To measure the frequency, you can either use the vertical cursors or the measurement provided by the oscilloscope.

We have a switching frequency just below the theoretical one (114 < 115.25), which is good for this step

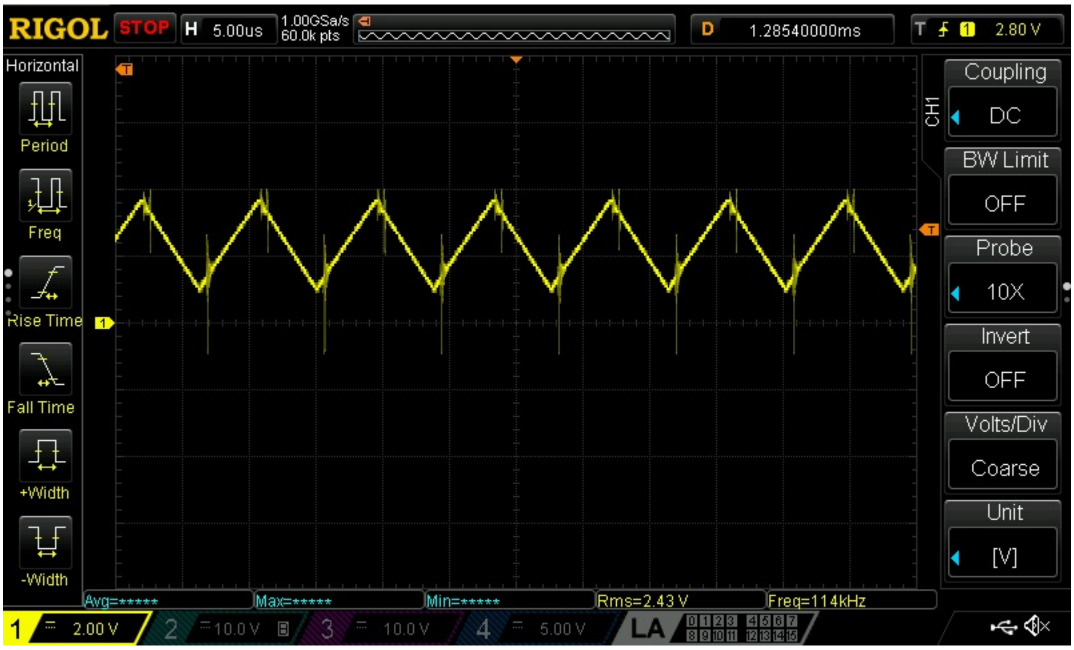


Figure 6 Oscilloscope capture of the switching frequency

$f_{sw,CF} = 114kHz$

/ 5 pt.

Q4: PWM MEASUREMENT AT THE MOSFET GATE

Screw the heatsinks to your devices (do not forget to add thermal paste between the surface of the heatsink and the MOSFETs). Put them in place and solder the MOSFETs (be careful not to damage them). Check the continuity with a multimeter and look for unintentional short circuits. Measure the PWM signal of the transistors (gate to source voltage) at minimum input voltage.

For this measurement, use two isolated voltage probes. Connect the first one between HVG and the source terminal of the high-side MOSFET (by properly connecting the terminals of the probe to the corresponding test points). The second probe is connected between LVG and the source terminal of the low-side MOSFET. Measure the frequency and dead time.

Provide the oscilloscope measurements of the PWM at the gate of the transistors, showing the frequency and the dead time.

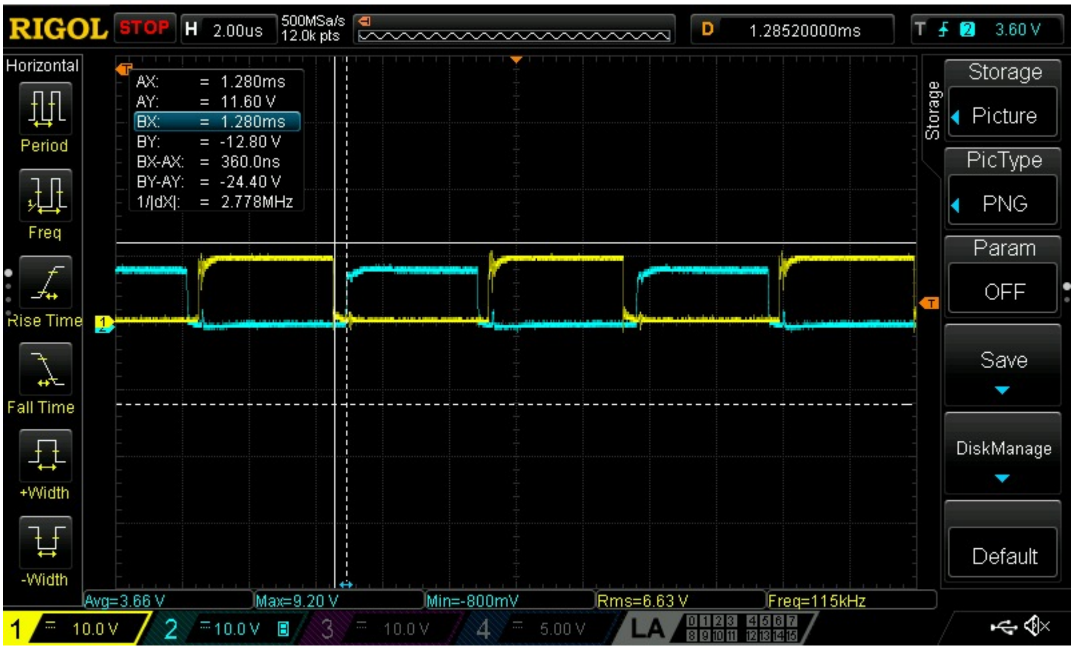


Figure 7 Oscilloscope capture of the PWM measurement at the MOSFET gate

$f_{PWM} = 115kHZ$ | $DT = 360ns$ | / 6 pt.

Q5: MEASUREMENT OF MIDDLE POINT VOLTAGE

Now test that your MOSFET are switching as expected. Test the middle-point connection to visualize the square-wave from the half-bridge. Connect an isolated probe between the drain terminal of the low-side MOSFET and the primary-side ground (by properly connecting the terminals of the probe to the corresponding test points).

Using a second isolated probe, test the high-side MOSFET connecting between the input voltage and the middle-point test points (drain-to-source of high-side MOSFET).

Provide the oscilloscope measurements and report the frequency of the middle-point signal and the maximum drain to source voltage of both the high-side and low-side MOSFETs.

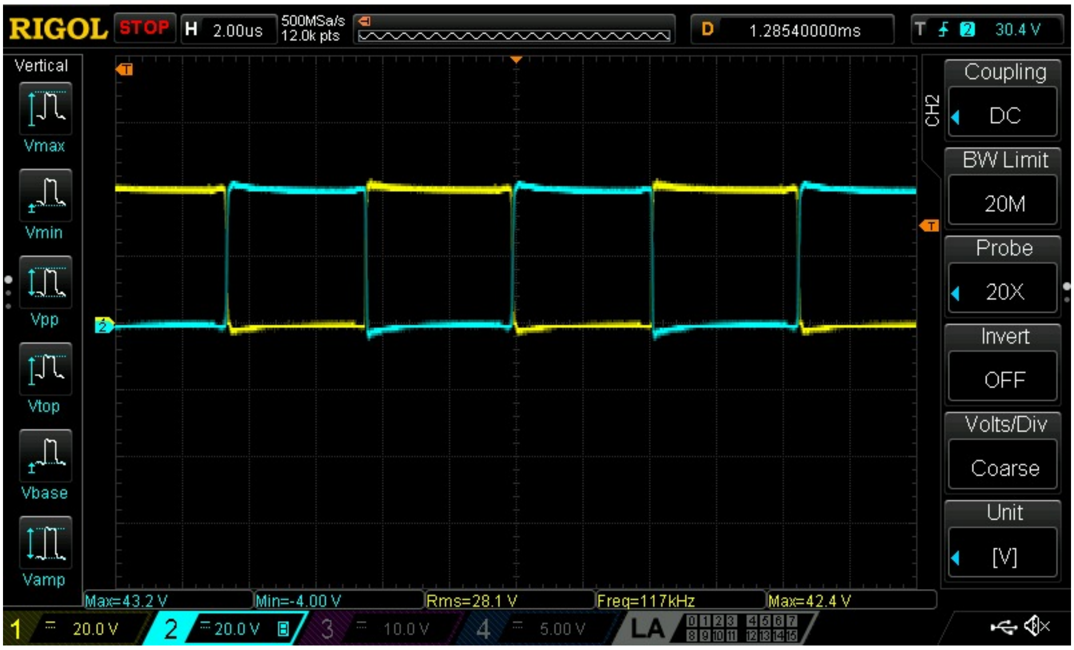


Figure 8 Oscilloscope capture of the Middle point voltage

$f_{PWM_{MP}} = 117kHz$	$V_{DS_{Q1}} max = 43.2V$	$V_{DS_{Q2}} max = 42.4V$	/ 6 pt.

RESONANT TANK AND TRANSFORMER

SOLDERING OF THE RESONANT TANK

Solder the resonant capacitor C_r, the external inductor L_r you built during report 2 (if applies), the current sensing wire to the pad connectors in the PCB (do not forget to terminate this wire in case you use Litz wires, leave enough space between the wire and the board to be able to connect a current probe) and the transformer.

Q6: MEASUREMENT OF THE MAGNETIZING CURRENT UNDER NO-LOAD CONDITION

After soldering, use the oscilloscope and a current probe to measure the magnetizing current when the secondary side of the transformer is not connected to any load. For this measurement, connect the input power supply and increase gradually the voltage to $V_{in} = 40\,V$. This current is measured by placing a current probe in the wire you have previously soldered to the pad connectors. Take into account the polarity of the current when placing the probe to obtain correct measurements.

Export the waveform of the magnetizing current from the oscilloscope and measure the RMS and the peak values of the current. Comment on the results and compare them with your previous simulation results.

<u>Note:</u>
Note that in open-loop conditions the IC L6599a will be switching at the minimum switching frequency, then you can only compare the magnetizing current at $V_{in} = 40\,V$.

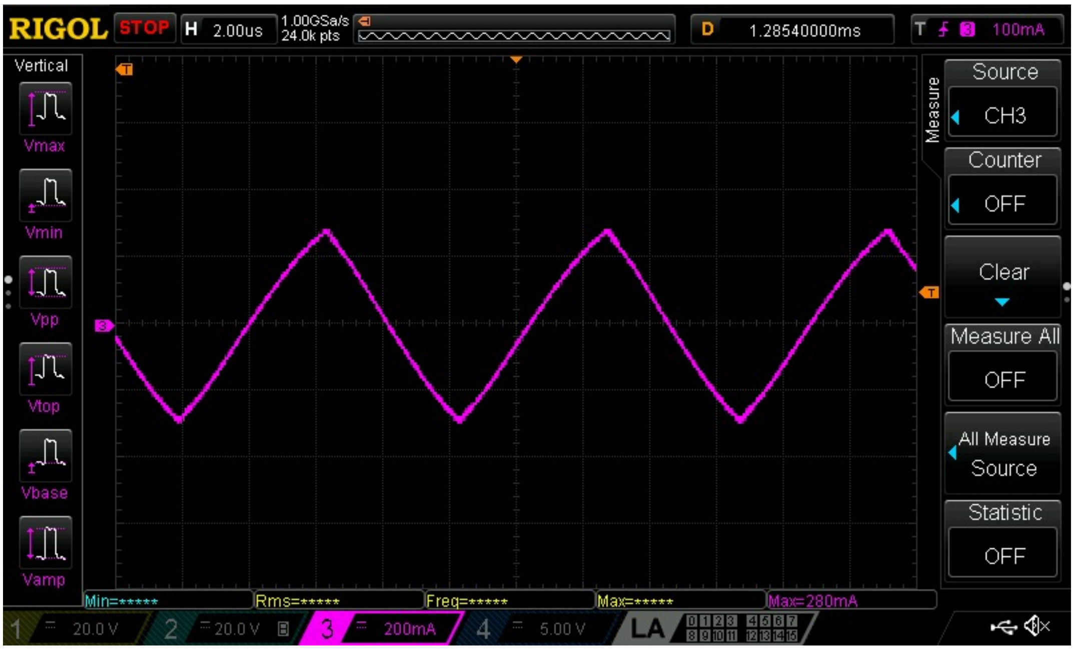


Figure 9 Magnetizing current under no-load condition

Figure 10 Magnetizing current under no-load condition (details)

$I_{Lm,RMS} = 178mA$	$I_{Lm,peak} = 280mA$	/ 6 pt.

Q7: MEASUREMENT PRIMARY AND SECONDARIES SIDE VOLTAGES

Use the same source configuration as in previous question (minimum input voltage and no-load condition). Once at a time, measure the primary side voltage, and then your secondary side voltages using isolated probes. Respect winding's directions as in Report 2. Show that the voltages are in phase as expected when measuring from the PCB test points. Provide oscilloscope acquisition of your primary and secondary sides voltages, then calculate the experimental transformer ration. Compare your results with the theoretical expected values.

$$V_S, max = n \cdot V_P, max \simeq 1.04 \cdot 50.4 = 52.416V$$

$$N_{real} = \frac{52.0}{50.4} = 1.0317$$

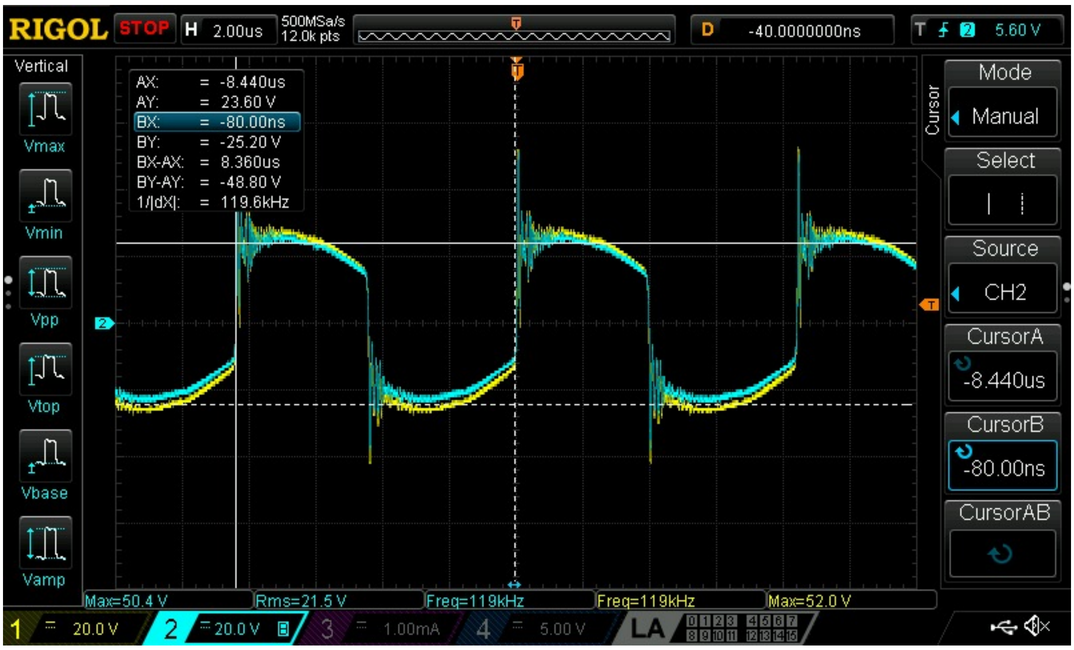


Figure 11 Primary and Secondary Voltage

$V_P, max = 50.4V$ $V_S, max = 52.0V$

$N_{theoretical} = 1.04$ $N_{real} = 1.0317$

/ 7 pt.

COMPENSATION NETWORK

SOLDERING THE COMPENSATION NETWORK COMPONENTS

Solder all the elements of compensation network, the error amplifier TL431 and the optocoupler LED protection circuit. Do not add the optocoupler in its socket yet.

Q8: MEASUREMENT OF THE OUTPUT DIVIDER

Connect the power supply to the output connector of your converter (leave input side disconnected). Make sure to connect power supply polarity correctly according to your design. Provide your nominal output voltage using the power supply. Measure the reference voltage that is provided to the TL431. Make sure that the reference voltage is exactly 2.5V or at least within the boundaries set by the TL431. Provide a picture of the voltage value with the multimeter/oscilloscope.

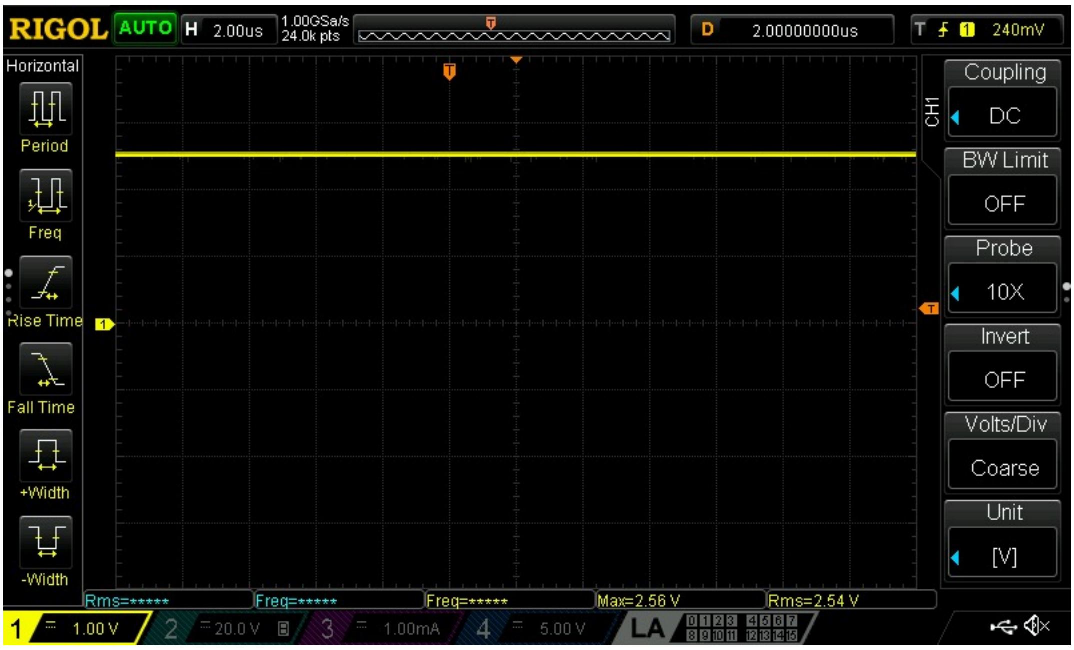


Figure 12 Measurement of the output divider

$V_{div,real} = 2.54V$

/ 5 pt.

Q9: VERIFICATION OF THE CONTROLLER SWITCHING FREQUENCY VARIATION UNDER EMULATED OUTPUT VOLTAGE

The purpose of this test is to verify that the control system is responding to the changes in the output voltage. In order to verify this, the additional power supply used in previous question will be used in the same way. The idea consists in emulating the output regulation of your converter by means of this power supply. When you intentionally vary the output voltage, you will be able to see how the controller responds by adjusting the switching frequency to modify the resonant tank's gain.

You need to measure at all the time the middle-point voltage and the output voltage. For this test you need to use one of the test setups that is equipped with two voltage sources.

First, plug in the optocoupler and connect one power supply to your input and one to your output. Set first the output voltage of the output power supply to your nominal output voltage. Then set the input voltage of the input power supply to $V_{in,nom}$. Report the frequency of the middle-point signal and the average value of the output voltage. Then increase the output voltage by 5% and report the frequency of the middle-point again. Finally, repeat the process decreasing the output voltage by 5%. At this point, you should be able to view how the intentional changes in the output voltage modifies the switching frequency of the controller. Comment on the results and provide waveforms of the three cases showing all the time, the output voltage and the middle-point signal.

We started having some trouble here. In order for this step to work, we had to bring the voltage up to ≈ 36V, to then plug the high-side mosfet. Afterwards we could then bring the voltage up to 40V and plug the optocoupleur in order to get this screen capture. Otherwise, the IC would always trigger its protection.

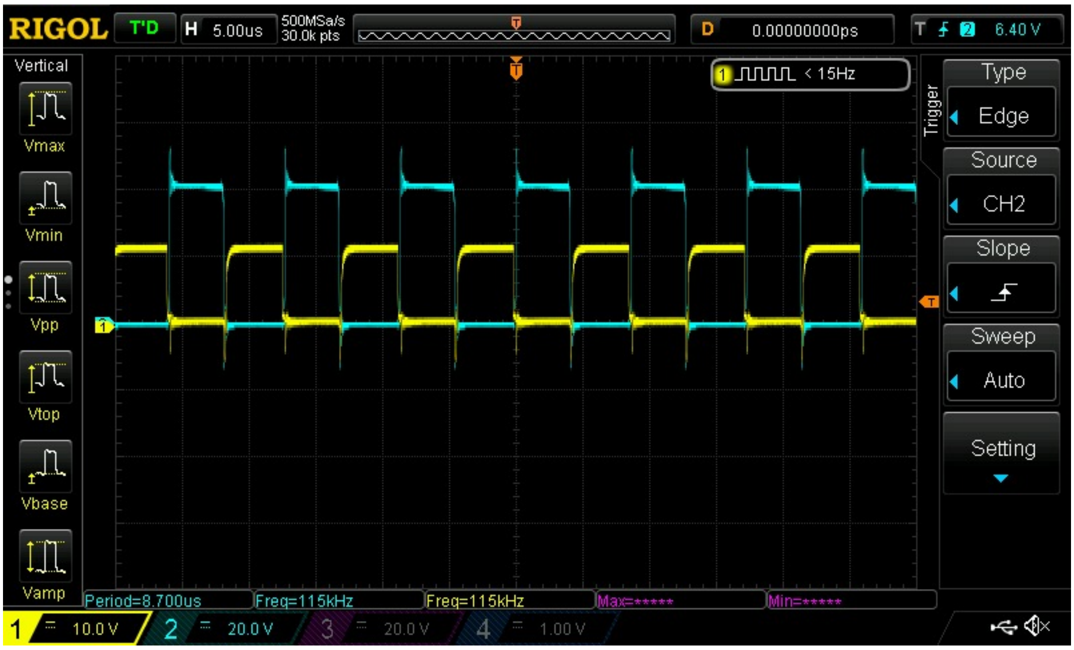


Figure 13 Oscilloscope capture of the High-Side and Low-Side Mosfet voltage (HVG) & (LVG)

f_{mid}, min = $115kHz$	$f_{mid}, +5\%$ =	$f_{mid}, -5\%$ =	/ 6 pt.

OPEN-LOOP TEST

SOLDERING SECONDARY SIDE COMPONENTS

Remove the optocoupler form its socket. Solder the diodes with its heat-sink (do not forget to add thermal paste between the surface of the heatsink and the diode) and the output capacitor/s.

Q10: VERIFICATION OF THE OUTPUT VOLTAGE AT THE MINIMUM FREQUENCY

After soldering, connect the power supply to provide the minimum input voltage to your converter. Additionally, use the active load and connect it to the output terminal of your PCB. Use the load function of the active load. Perform the test at 25W and 50W (increase the power gradually). Using the oscilloscope, measure the output average voltage of your converter as well as the peak-to-peak ripple voltage.

With this test, you will verify the functionality of your converter in an open loop at up to full load. Start by increasing the input voltage from 0 to $V_{in,min}$ gradually. Export the waveform of the output voltage measurements from the oscilloscope and measure ripple at $V_{in,min}$, explain the behaviour you observe.
Report oscilloscope acquisition for both power levels. Fill the answers boxes only with data relative to the full power ($50W$) tests at $V_{in,min}$.

We managed to get a quick capture of a 22V output voltage but shortly after, the IC would go in protection.

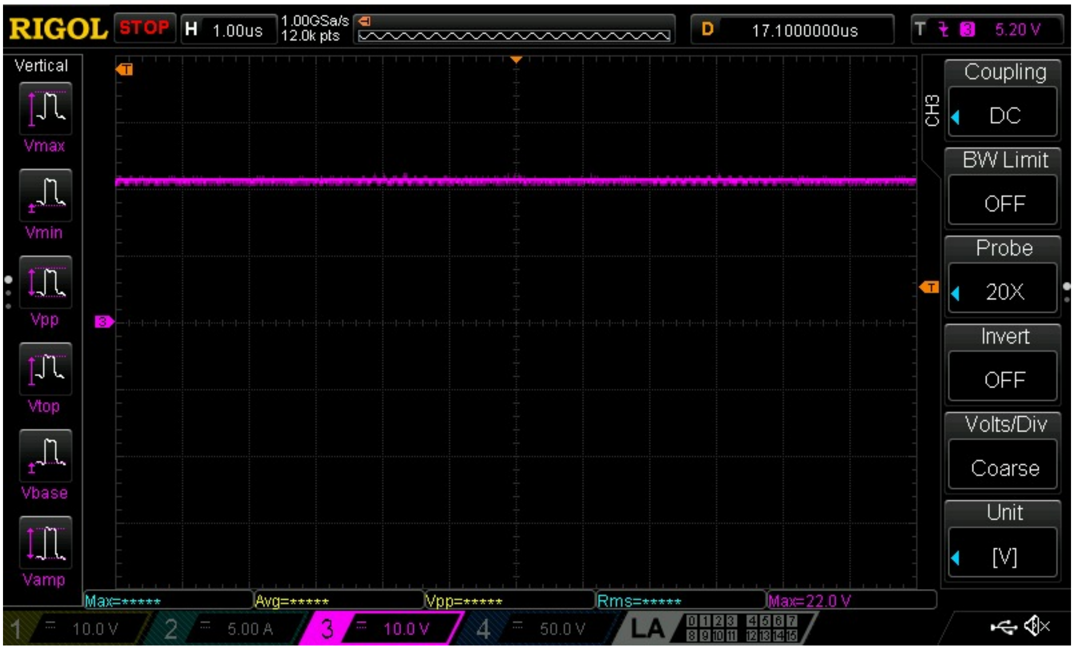


Figure 14 Oscilloscope capture of the output voltage

$V_{out,avg} = 22V$	$V_{out,ripple,pp} =$	/ 9 pt.

Q11: TEST OF THE OUTPUT VOLTAGE AT NOMINAL INPUT VOLTAGE

Similar to the previous question, use the same test setup to measure the output voltage and the voltage ripple at the nominal input voltage. Start by increasing gradually the input voltage from 0 to $V_{in,nom}$. Perform the test at 25 W and 50 W. Export the waveform of the output voltage measurements from the oscilloscope and measure ripple at $V_{in,nom}$, explain the behavior you observe.
Report oscilloscope acquisition for both power levels (25 W and 50 W). Fill the answers boxes only with data relative to the full power (50 W) tests at $V_{in,min}$.

We can see here that we are in burst mode and again, shortly after that the IC went in protection

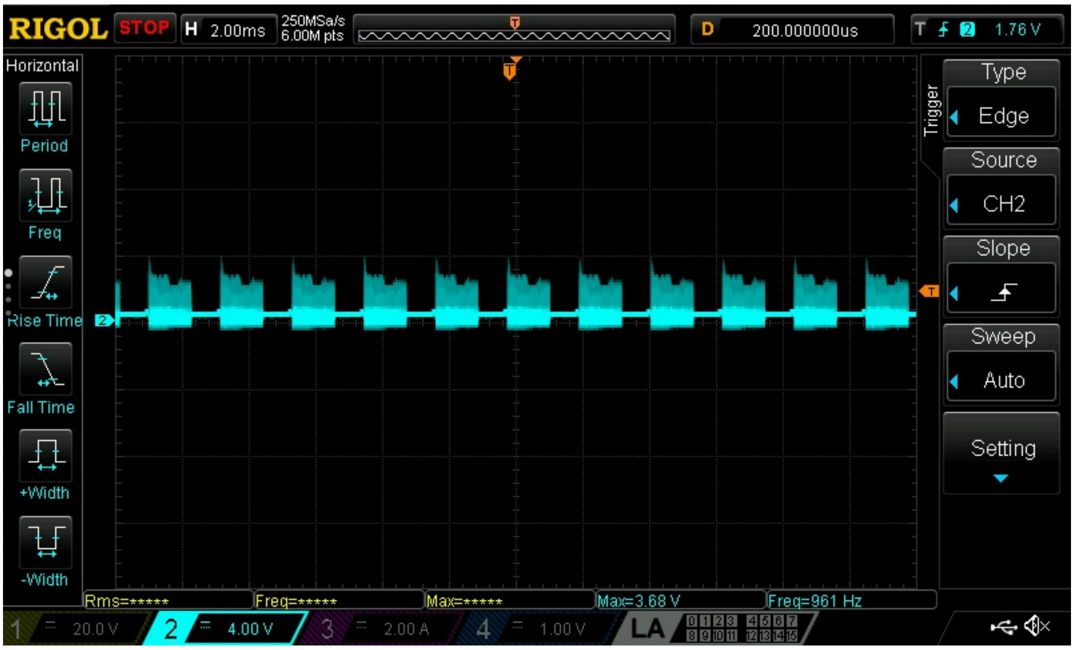


Figure 15 Oscilloscope capture of the middle-point signal

$V_{out,avg} =$	$V_{out,ripple,pp} =$	/ 7 pt.

CLOSED-LOOP TEST

Now plug in the optocoupler in its socket. In this test, the whole operation of the converter will be validated. The test consists in validating the operation of the converter in closed-loop at the following power ratings: 25%, 50% and 100% of the rated power.

For these set of tests, you need to measure at any time: 1) the middle-point voltage, 2) the magnetizing current and 3) the output voltage. Report oscilloscope acquisition for all the three power levels. Fill the answers boxes only with data relative to the full power ($50W$) tests.

Q12: REGULATION VERIFICATION AT THE MINIMUM INPUT VOLTAGE

To run this test, follow the steps below:

1. Connect the active load to the output and set it to $P_{out} = 0W$ (no-load condition).
2. Connect the input DC supply and increase the input voltage gradually until reaching $V_{in} = 40\,V$. Verify that the converter is switching properly by looking into the middle-point voltage.
3. Increase gradually the output power so that the converter provides $12.5W$.
4. After confirming the converter's operation, increase the output power to $P_{out} = 25W$ and finally to $P_{out} = 50W$ (full-load condition).
5. As the converter is operating, monitor at any time temperature with the thermal camera.
6. Save wave-forms and report results.

As for the previous question, the only thing that we could capture was during burst mode, after what the IC would shut off again.

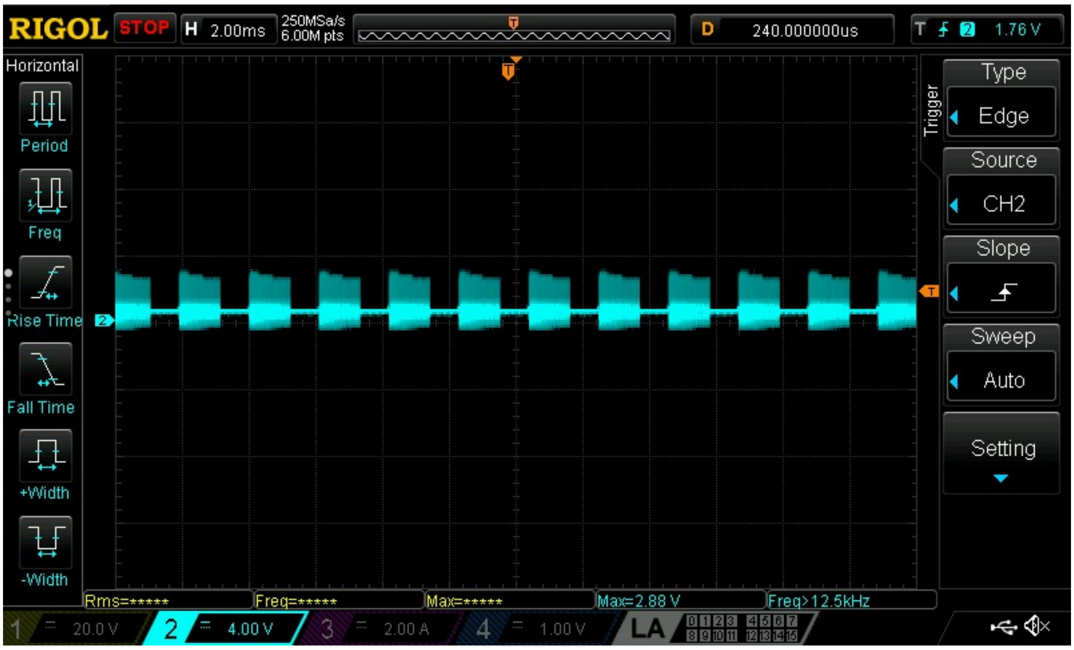


Figure 16 Oscilloscope capture of the middle-point signal

$f_{sw,midpoint} =$

$V_{out}(avg) = 0V$ $V_{out,ripple,pp} = 0V$

$I_{Lm,RMS} =$ $I_{Lm,MAX} =$ / 8 pt.

Q13: REGULATION VERIFICATION AT THE NOMINAL INPUT VOLTAGE

Repeat the same steps from the last question for $V_{in} = 45\,V$.

The same issue/result occured at nominal input voltage

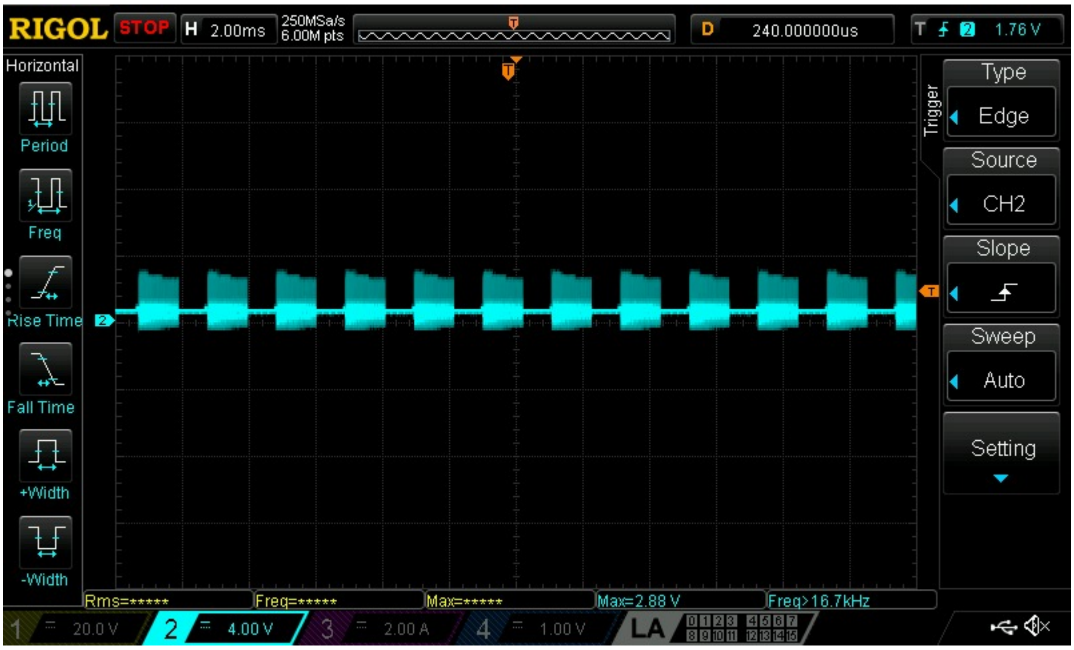


Figure 17 Oscilloscope capture of the middle-point signal

$f_{sw}(mid) =$

$V_{out}(avg) = 0V$

$V_{out,ripple}(pk-pk) = 0V$

$I_{Lm}(RMS) =$

$I_{Lm}(pk) =$

/ 8 pt.

Q14: REGULATION VERIFICATION AT THE MAXIMUM INPUT VOLTAGE

Repeat the same steps from the last question for $V_{in} = 50\,V$.

At 50V, we captured a different waveform, but it was still in burst mode and the IC shut off immidiately after that.

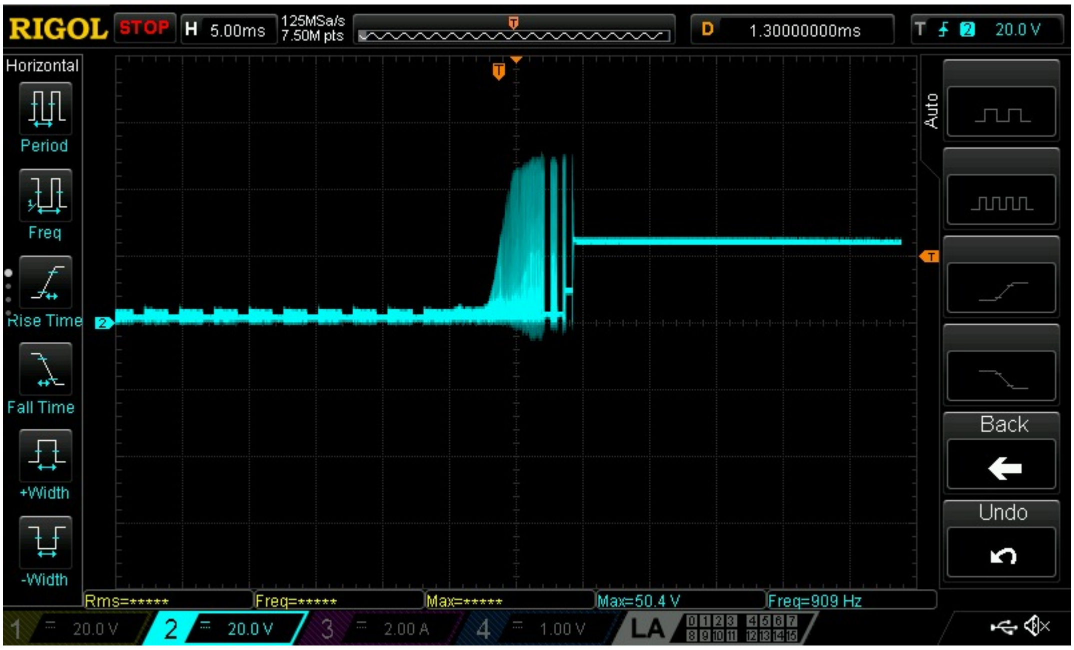


Figure 18 Oscilloscope capture of the middle-point signal

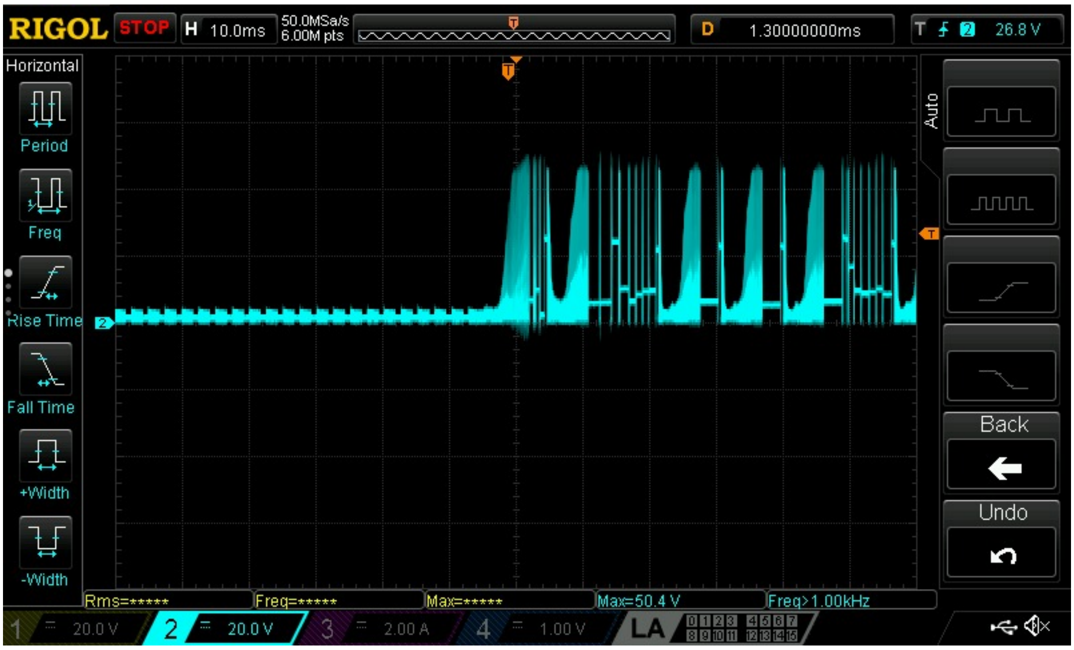


Figure 19 Oscilloscope capture of the middle-point signal

Figure 20 Oscilloscope capture of the middle-point signal

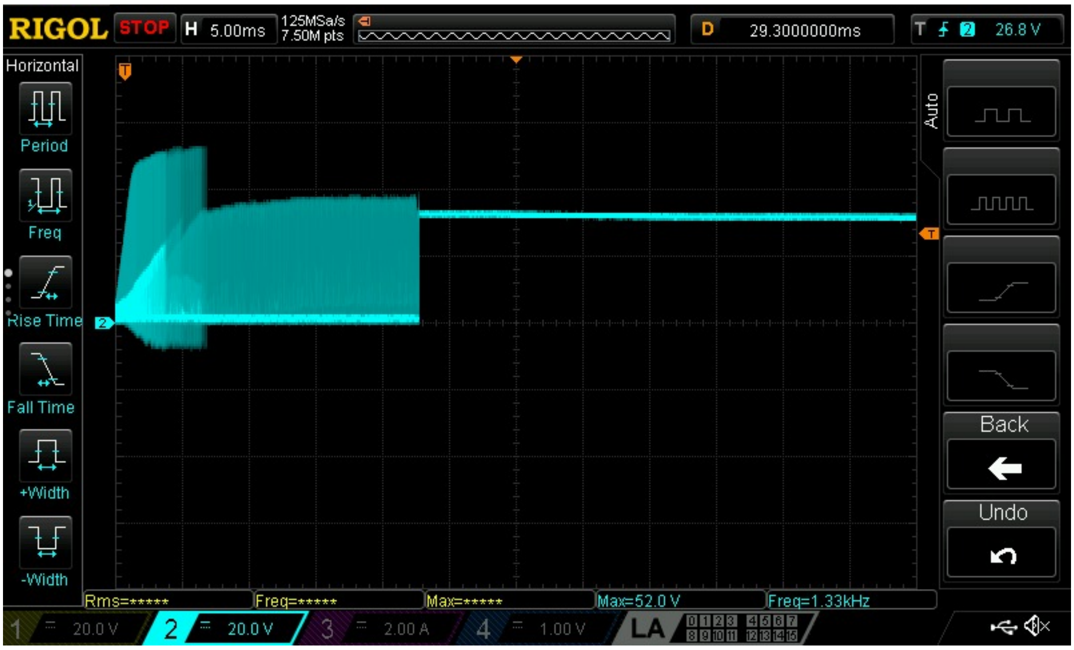


Figure 21 Oscilloscope capture of the middle-point signal

$f_{sw}(mid) =$

$V_{out}(avg) = 0V$ $V_{out,ripple}(pk-pk) = 0V$

$I_{Lm}(RMS) =$ $I_{Lm}(pk) =$ / 8 pt.

LOOP STABILITY MEASUREMENT

The stability and robustness of the voltage control can be tested with the Omicron Lab Bode 100 multifunctional test set. This test is based on the injection of a small perturbation between the real output voltage terminal and the output voltage measurement used for the closed-loop voltage control, and on the measurement of the corresponding effects on the control loop.
Useful information can be found in the application notes *DC/DC Converter Stability Measurement*, *Loop Gain Measurement - The Voltage Injection Method using the Bode 100 and the B-WIT 100* and in the *Bode 100 User Manual*.

Disable the primary-side power supply and the output-side active load.
Disconnect the jumper on the injection resistance R_{inj} (10Ω).
Connect as follows:

- The output of the B-WIT 100 Wideband Injection Transformer to the jumper (red connector on the V_{out})
- The channel 1 probe to the side of the R_{inj} jumper connected to R_{RH} and to the ground (be careful not to create short circuit with the other leg of the jumper, if you want to have a more stable connection you can remove the black plastic part of the jumper)
- The channel 2 probe to V_{out} test point and to secondary ground

Be aware that this test can only be performed in some of the testing stations.

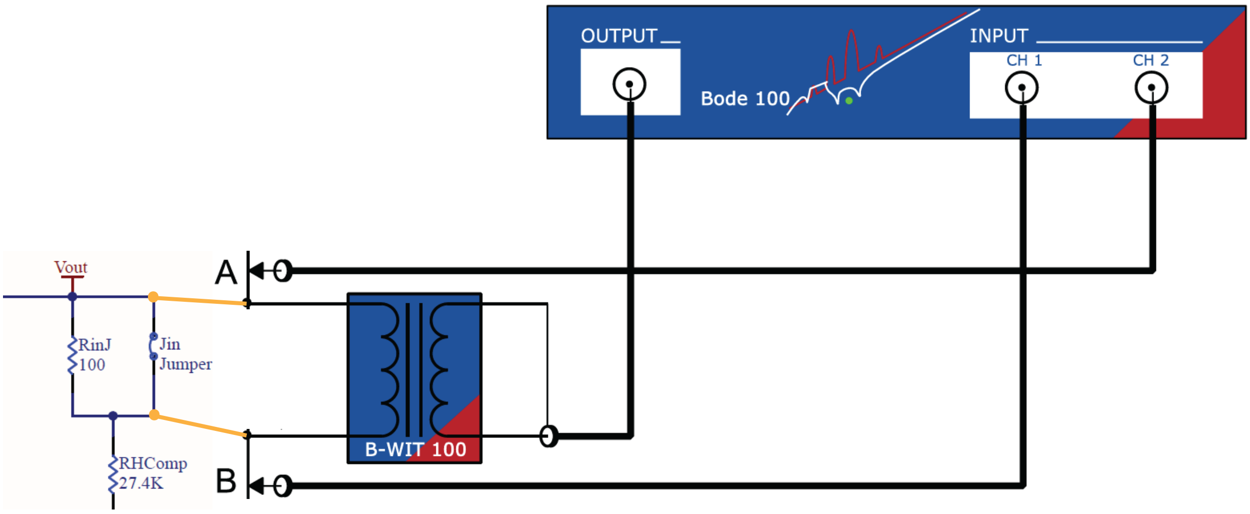


Figure 22 Injection schematic

Connect the Bode 100 to the PC, turn it on and open the program *Bode Analyzer Suite*. Select the "Gain/Phase" measurement mode. Check in the "Hardware Setup" page that both Input 1 and Input 2 of the Bode 100 are set in "High Impedance" mode. Set the injection frequency sweep from 100 Hz to 1 MHz and the Source Level to -20 dBm.

Q15: LOOP STABILITY IN THE NOMINAL OPERATING POINT

Set the active load in CR "resistive mode" and choose the resistance in a way to absorb the nominal power $P_{out} = 50\,\text{W}$ when the converter output voltage V_{out} is at its nominal value.

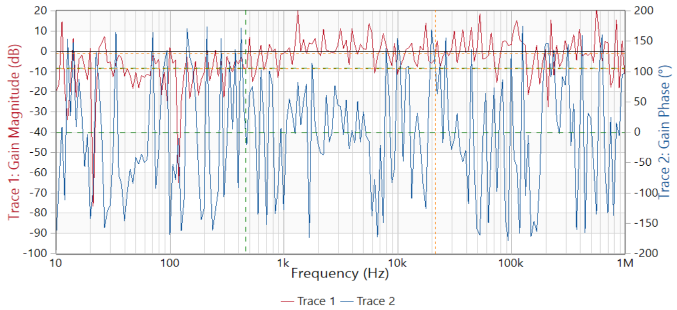
Enable the active load and the primary-side power supply, and set the input voltage to $V_{in} = 45\,\text{V}$.

In the Bode Analyzer Suite, enable the continuous injection of the perturbation voltage, and monitor the results. In case the results are too noisy, increase the Source Level value. In case the "Receiver Overload" message is displayed, change the "Attenuator Levels" of the receivers.

Export the results and process them offline. Draw the bode plot of the measured Loop Gain and check the crossover frequency f_{bw}, the phase margin φ_m, and the gain margin G_m.

Compare the results with the theoretical values you aimed for according to the hints given in report 3.

Measurement: Gain / Phase



	Cursor 1	Cursor 2	Delta C2-C1
Frequency	464,159 Hz	21,544 kHz	21,08 kHz
Trace 1	**Magnitude (dB)**	**Magnitude (dB)**	**Magnitude (dB)**
Measurement	-8,364 dB	-1,14 dB	7,224 dB
Trace 2	**Phase (°)**	**Phase (°)**	**Phase (°)**
Measurement	-1,151 °	104,898 °	106,049 °

Sweep	
Start frequency:	10 Hz
Stop frequency:	1 MHz
Center frequency:	500,005 kHz
Span:	999,99 kHz
Sweep mode:	Logarithmic
Numer of points:	201

Hardware setup	
Device type:	Bode100R1
Serial number:	LM409C
Receiver bandwidth:	1 kHz
Output level:	-20 dBm
DUT settling time:	0 s

Calibration	Full-Range	User-Range
Gain	-	-

Termination	Channel 1	Channel 2
Gain	1 MΩ	1 MΩ

Attenuator setting	Channel 1	Channel 2
Transmission	20 dB	20 dB

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Figure 23 Bode plot of the measured Loop Gain

f_{bw} = | φ_m = | G_m = | / 7 pt.

EFFICIENCY MEASUREMENTS

Once the converter's functioning has been verified, it is possible to evaluate its energetic performance.

Turn on the power analyzer. Set the coupling to "dc" and add the measurement of the efficiency as "phase/next phase". Set the display in "three-phase mode". The converter input variables and the energetic efficiency can be read from the "Phase 1" column, while the converter output variables can be read from the "Phase 2" column of the display. Discard the reading displayed in the "Phase 3" column.

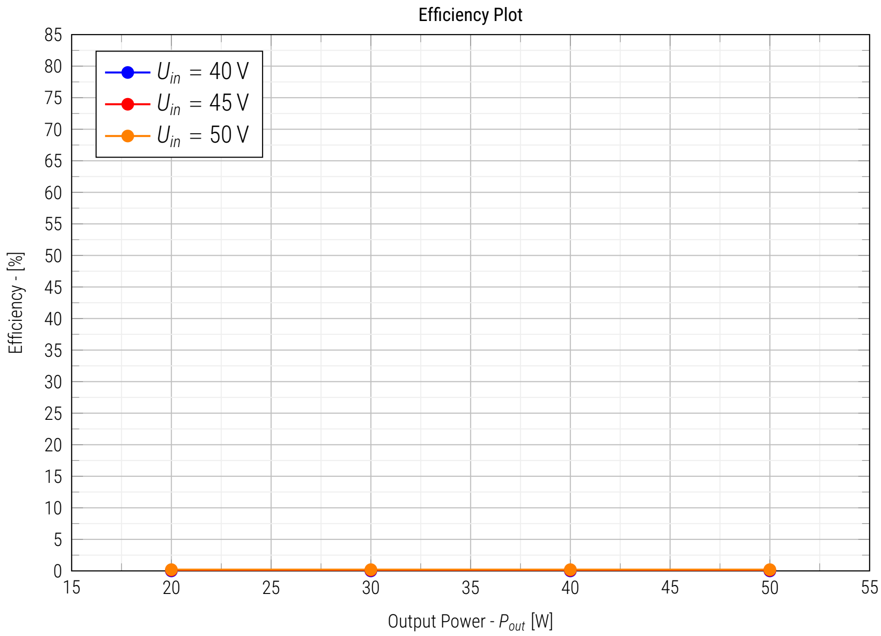
Q16: EFFICIENCY PLOT

Turn on the input power supply and the active load. Fill the table below with the efficiency measurements in the listed operating conditions. Then, include an efficiency plot of your results.

Unfortunately, we weren't able to output any power

Table 1 Efficiency Measurements.

V_{in} (↓) P_{out} (→)	20 W	30 W	40 W	50 W
40 V	0%	0%	0%	0%
45 V	0%	0%	0%	0%
50 V	0%	0%	0%	0%



/ 10 pt.

Q17: ANALYSIS OF THE POWER LOSSES

Considering the converter nominal operating point (i.e., with V_{in} = 45 V and P_{out} = 50 W), compute the power losses and estimate the different contributions (you can use your calculations in previous reports as a reference). Explain how each different contribution has been estimated from the available measurements.
Fill in the table below and the corresponding pie chart.

Then, suggest a possible way to modify the design in a way to reduce the losses and improve the efficiency of the converter.

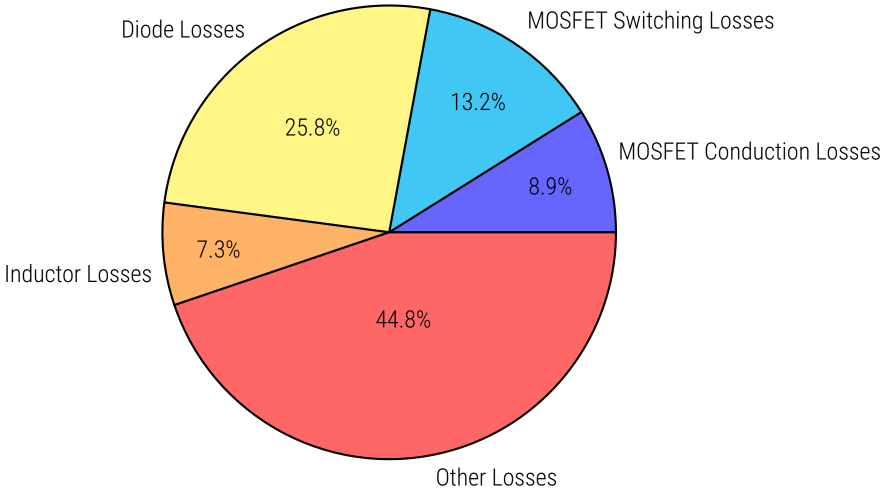
$$P_{R_{in}} = \frac{V_{in}}{R_{in}} = \frac{(45V)^2}{5k\Omega} = 0.405W$$

$$P_{R_{Zenner}} = \frac{V_{in} - V_Z}{R_{in}} = \frac{(45 - 15V)^2}{2.2k\Omega} = 0.409W$$

$$P_{R_S} = R_S \cdot I_{RMS}^2 = 150m\Omega \cdot (3.05A)^2 = 1.395W$$

Table 2 Power Losses Contributions.

Total Power Losses	4.931 W	100%
MOSFET Conduction Losses	0.44 W	8.9%
MOSFET Switching Losses	0.65 W	13.2%
Diode Losses	1.272 W	25.8%
Inductor Losses	0.36 W	7.3%
Other Losses	2.209 W	44.8%



/ 7 pt.

THERMAL MEASUREMENTS

The last step of the testing is to verify the thermal capabilities of the converter.

Q18: THERMAL MEASUREMENT AT THE NOMINAL OPERATING POINT

Set up the converter to work at its nominal operating point (V_{in} = 45V and P_{out} = 50W). Let the LLC converter operate for 10 min. Do not leave your converter unattended.

Measure with the thermal camera the temperature of the components on the PCB comprising your converter. Include the captured thermal image in your answer, and identify the component(s) with the highest temperature(s) and explain why exactly is this the case.

As our converter didn't output any power, componenets weren't heating. Otherwise, we would have expected the tranformer, external inductance and shoktty diodes to be the primary source of heat.

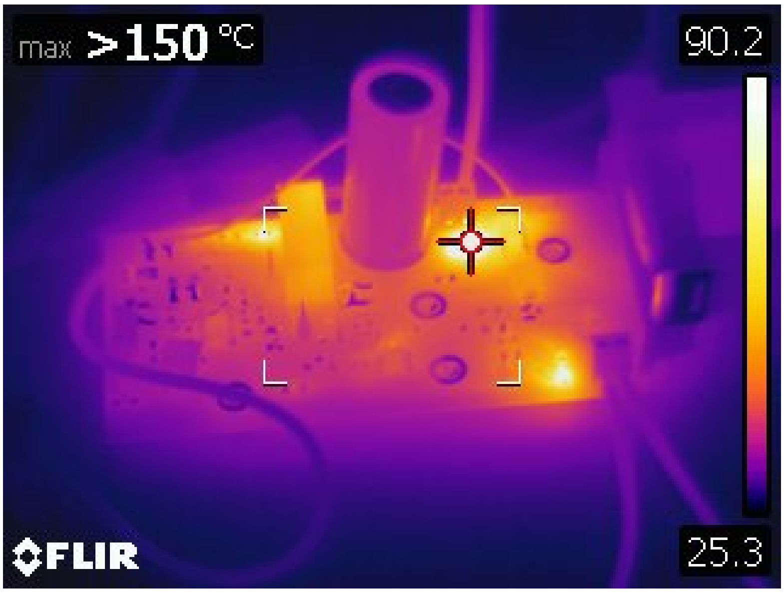


Figure 24 Thermal image of the boost converter.

T_{max} =

/ 9 pt.