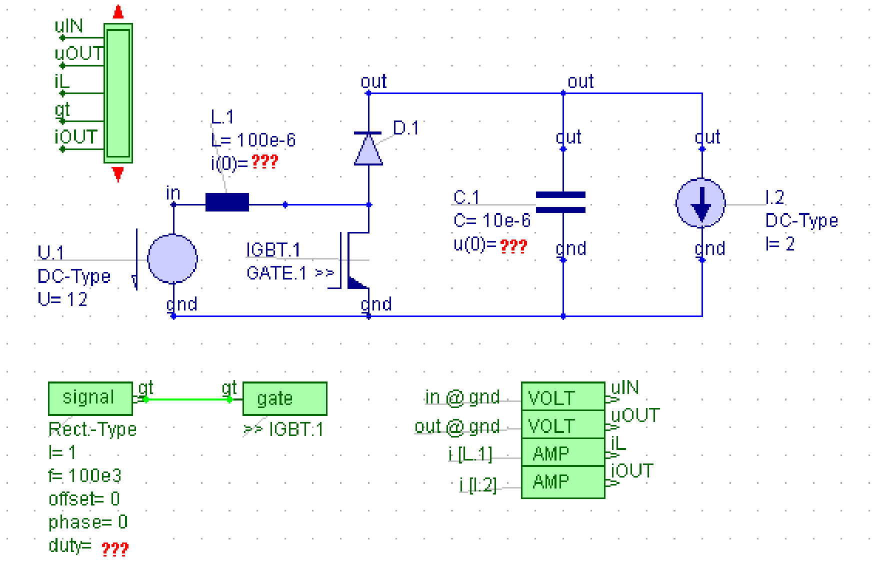
Exercise A: Buck-Converter

Here, we examine the behavior of the Buck-Converter from the figure below, whose input is modeled via an ideal 12V voltage source. The converter output is a load resistor R_{Load} and an output capacitor C_{out} with an equivalent series resistance R_C . The Buck-Converter choke is an ideal inductor L with a series resistance R_L . The switching frequency is fixed at f_S = 100 kHz.



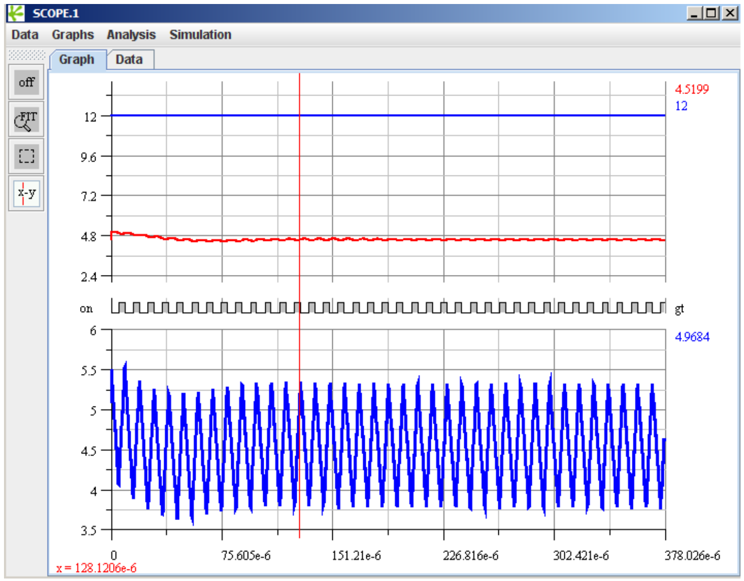
Build a simulation model of the Buck-Converter in GeckoCIRCUITS. Please use the component values as given in the circuit sheet. Plot the following converter variables within the GeckoCIRCUITS scope: Output voltage, u_{OUT}, input voltage u_{IN}, inductor current i_L and the gate signal *gt* of the switch. Please familiarize yourself with the various plotting settings of the GeckoCIRCUITS scope: You can plot several curves within a single graph, vary the curve colors, or set the plotting mode to "digital" for the gate signal. The labels in the graphs will be set according to the labels that you apply in your circuit sheet.

For the exercise parts 1 to 5, you shall assume that the converter operates in continuous conduction mode.

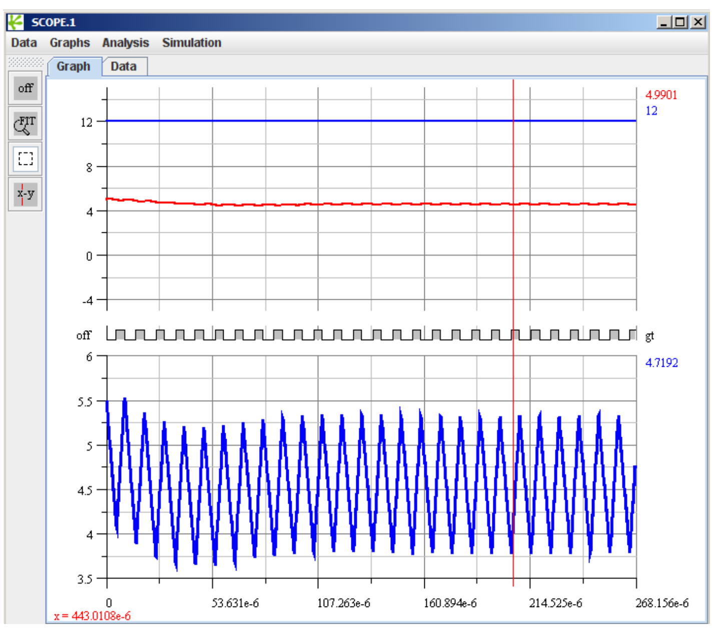
1. Calculate the value of the duty ratio *D*, so that the average output voltage is U_{out} = 5 V in the stationary state. Insert your calculated value of *D* into the model and verify the output voltage in your simulation. You can try to set the initial values of the output capacitor and the choke to the correct values, so that the circuit is already in steady-state.

   Try to find out the reason for the deviation of the output voltage from 5V by varying the corresponding simulation parameters, e.g. the diode and switch conduction resistances or the diode forward voltage drop. Please also ensure that the simulation step-width (which is set to 1sec as default value) does not have an influence on your simulation. Probably, you have to decrease the simulation step-width value.

Solution: $D = \frac{U_{aus}}{U_{DC}} = 0{,}417$ $\qquad I_{L0} = \frac{U_{aus}}{R_{Last}} = 5\ A.$

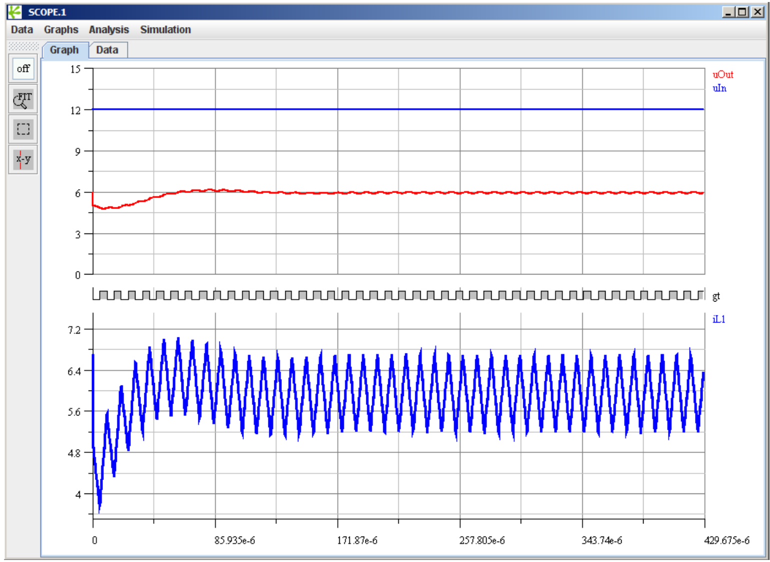


The output voltage U_{aus} as well as the current I_{L0} are both a little bit lower than 5 V and 5 A. The reason is the diode forward voltage drop of 0.6 V. When you decrease the diode forward voltages to 0 V, you will get approximately accurate values:



2. Now, set the duty ratio to $D = 0.5$. How does the output voltage U_{out} change? Verify your answer in a simulation.

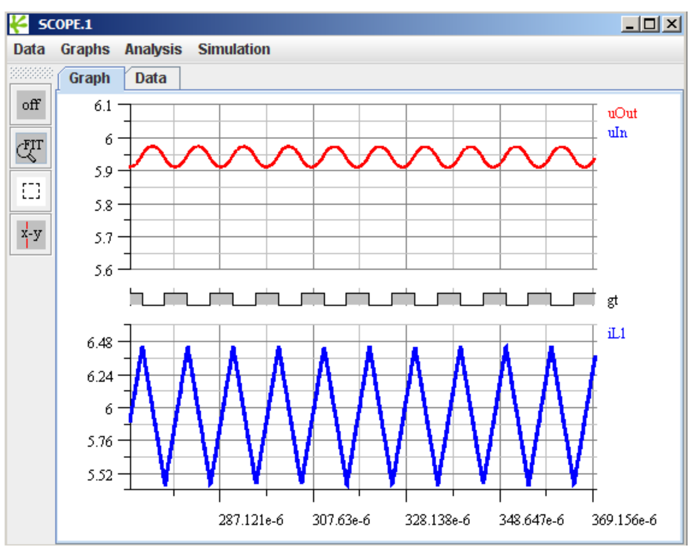
U_{out} = DU_{DC} = 6 V, the output voltage increases from 5 V to 6:*



3. In a next step, we want to limit the choke current ripple to i_L = 1 A (peak-to-peak). Calculate the required inductance value *L* and simulate the model. Please consider that the current ripple is dependent on *D*. Therefore, you can assume the "worst case" value for D.

   For the ripple current in the continuous conduction mode, the following equation holds: $\Delta i_L = \frac{U_{DC}}{L \cdot f_S} \cdot D \cdot (1 - D)$*, where the maximum ripple current appears at a duty ratio of D = 0.5. Hence, we can calculate the inductance as*

$$L = \frac{U_{DC}}{\Delta i_L \cdot f_S} \cdot D \cdot (1 - D) = 3 \cdot 10^{-5} H.$$

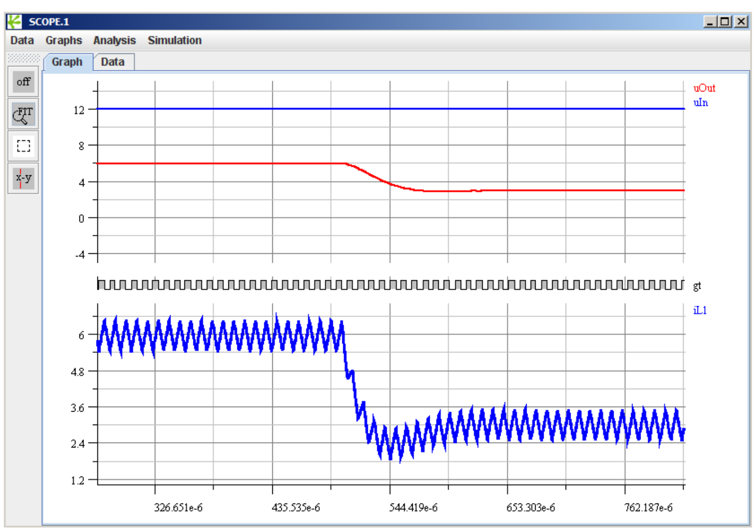


4. In the following, we consider the non-ideality of the choke. We assume R_L = 1 Ω. How does the output voltage u_{out} change? Also have a look at the shape of the choke current i_L. Would such a choke with a 1 Ω series resistance be useful/reasonable for this application?

Since the mean voltage across the inductor has to be zero in steady state, the output voltage can be calculated via a voltage divider, which is formed by the load resistor and the inductor resistance: $U_{out} = \frac{R_{Load}}{R_L + R_{Load}} \cdot D \cdot U_{DC} = 3V.$

Within GeckoCIRCUITS, you can visualize a change of component value with the help of the "break-function": In the "Simulation→Parameter" menu, you can set a break time t_{br}, which defines a time when the simulation should stop during the whole simulation run. After the simulation break, you can change the component value and continue your simulation.

The mean value of the inductor current is decreasing, whereas the size of the current ripple stays more or less constant.



In practice, an inductor where the series resistor is of comparable size as the load resistor would be not approproate, since, for instance, the output voltage is getting dependant from the output load resistance.

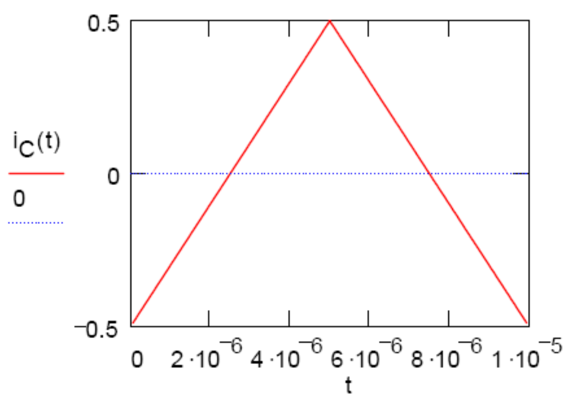
5. Set the resistance value back to $R_L = 0$. Calculate the output capacitance value C_{out} so that the maximum voltage ripple of the output voltage u_{out} is limited to u_{aus} = 50 mV (peak-to-peak).
   Hint: To calculate the capacitor value, you can assume that the output voltage u_{aus} (and therefore also the resistor current) is constant as a good approximation. Using the current of the capacitor C_{out}, you can calculate the charge that is responsible for the output voltage ripple u_{out} . Hence, you can calculate the ripple current in a good approximation.

The maximal ripple current appears with a duty ratio of D = 0.5 and can be calculated via the capacitor charge

$$i_C = i_L(t) - i_{Load}(t).$$

Assuming a constant output current, the equation fort he capacitor is simplified to

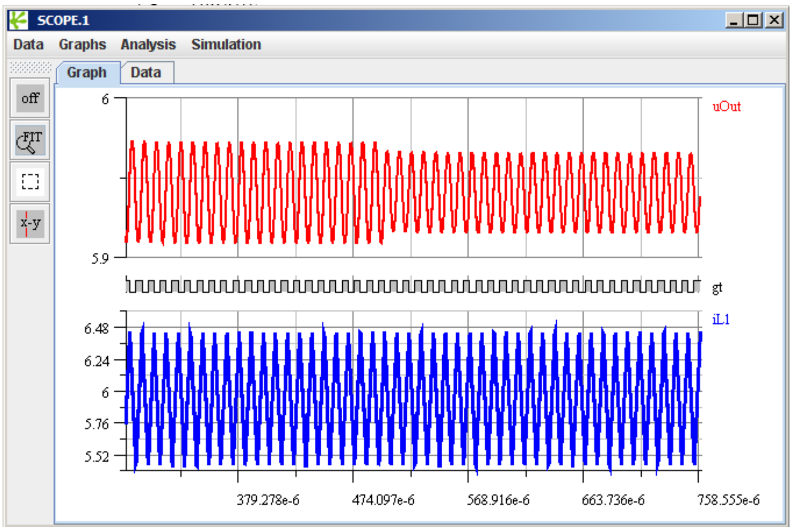
$$i_C(t) = i_L(t) - I_{Load}.$$



The charge that is stored in the capacitor is increasing with a positive current, and the maximal change of charge can be calculated by the equation

$$\Delta Q = \int_{t_1}^{t_2} i_C(t)dt = 1{,}25 \cdot 10^{-6} C, \qquad t_1 = \frac{D \cdot T_S}{2}, \qquad t_2 = D \cdot T_S + \frac{(1-D) \cdot T_S}{2}$$

Considering the given maximum voltage ripple, we calculate the required capacitance value as $C = \frac{\Delta Q}{\Delta u_{aus}} = 25\ \mu F$.



In the next tasks, the Buck-Converter shall operate in the discontinuous conduction mode. Assume a value of R_{Load} = 20 Ω and a capacitance of C_{out} = 20 F.

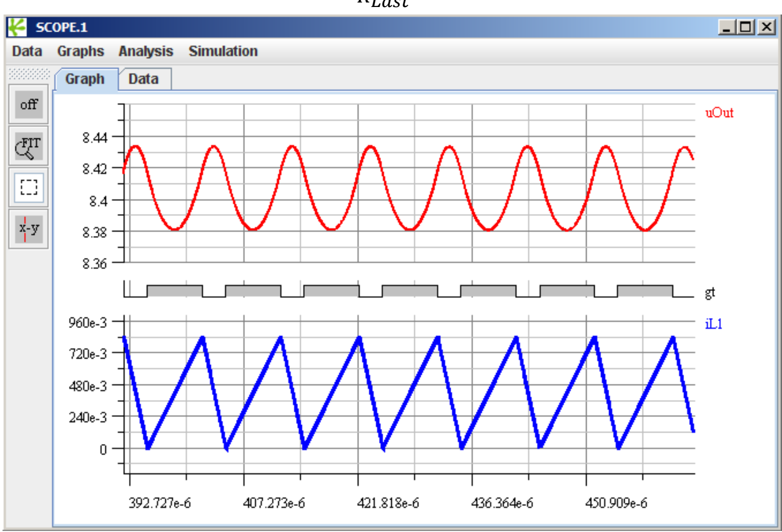
6. Calculate the duty ratio D_{limit} for the Buck-Converter, so that the circuit operates at the limit between continuous and discontinuous conduction mode. Insert your result into GeckoCIRCUITS and check your result.

Since the converter is operating at the limit between continuous and discontinuous conduction mode, we can use the equations for the continuous operation:

$$\Delta i_L = \frac{U_{DC}}{L \cdot f_S} \cdot D_{Grenze} \cdot (1 - D_{Grenze}) = 2 I_L = 2 \cdot \frac{U_{aus}}{R_{Last}} = 2 \cdot \frac{D_{Grenze} \cdot U_{DC}}{R_{Last}}.$$

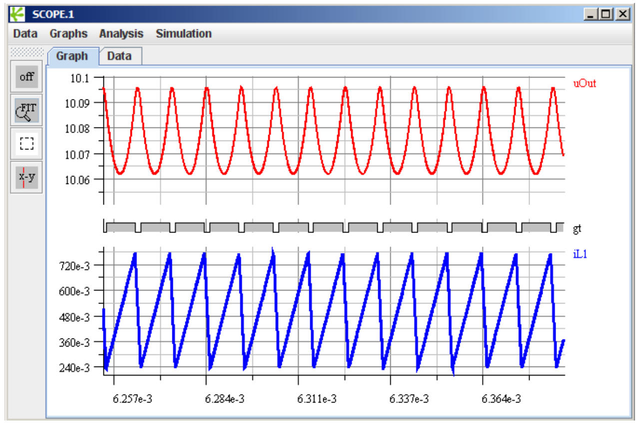
With this result, we can calculate the limit duty ratio D_{limit}:

$$D_{limit} = 1 - \frac{2 \cdot L \cdot f_S}{R_{Last}} = 0.7.$$



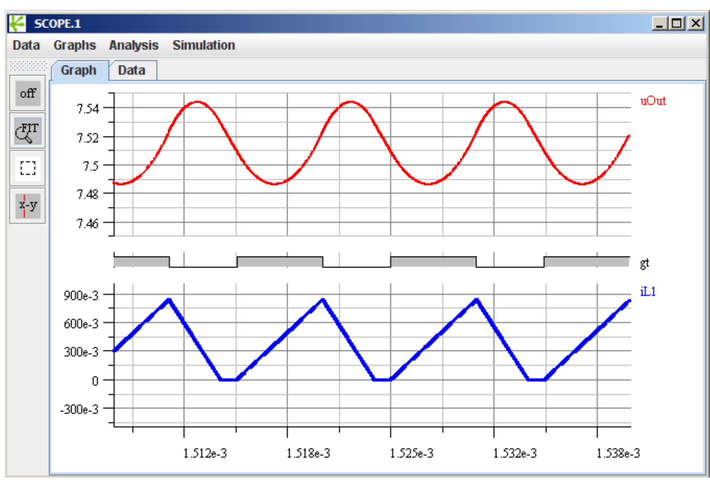
7. Try to increase and decrease the duty ratio by 20% in each case. How does the model behave – consider especially the time needed for the model to reach steady state. Can you explain this behavior?

   a) D=0.84 – The buck converter operates in the continuous mode; since the load resistance is quite large, it takes a while until the converter reaches steady state.



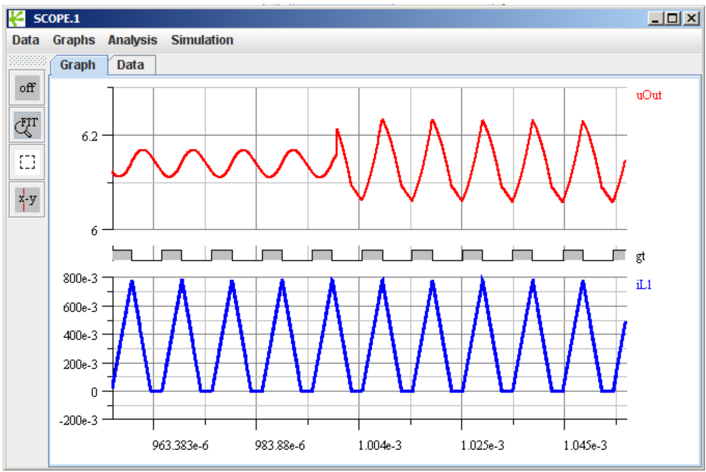
   b) D=0.56 – Now, the converter operates in continuous disconduction mode. At simulation startup, the simulation reaches steady state quite fast. The reason is that the ringing is surpressed during the time interval when the inductor current is zero.

c)



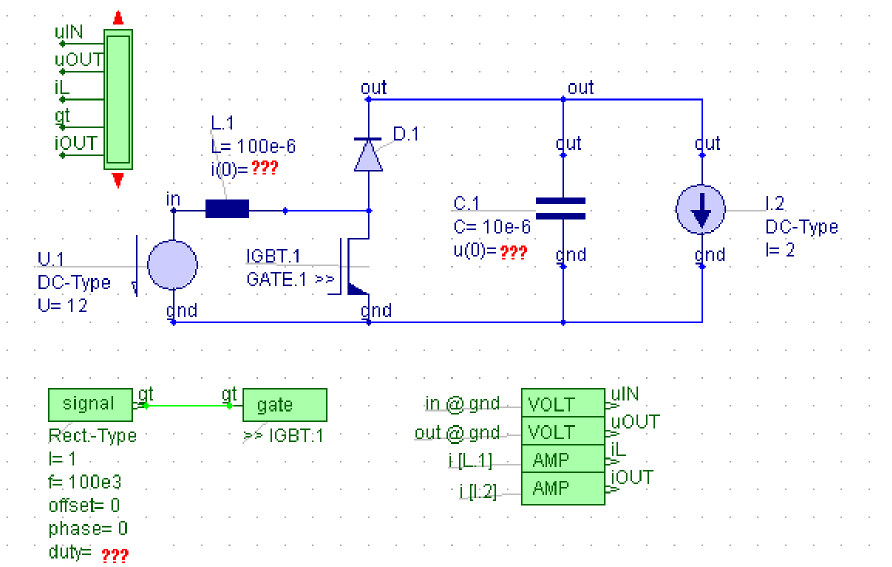
8. Now, set D = 0.4. Compare the output voltage u_{out} for the cases R_C = 0 and R_C = 0.2 . You can visualize the difference between the selected duty-ratios within one simulation in the scope by using the "Simulation->Parameter->t_{break}" function.

   D = 0.4 – Since the ripple current is flowing nearly completely via the capacitance, the equivalent series resistance generates a voltage drop, which increases the output voltage ripple.



Exercise B: Boost-Converter

Using the available 12 V DC voltage source, we want to produce a constant 50 V output voltage. Therefore, we use the ideal boost-converter model as shown in the figure below.

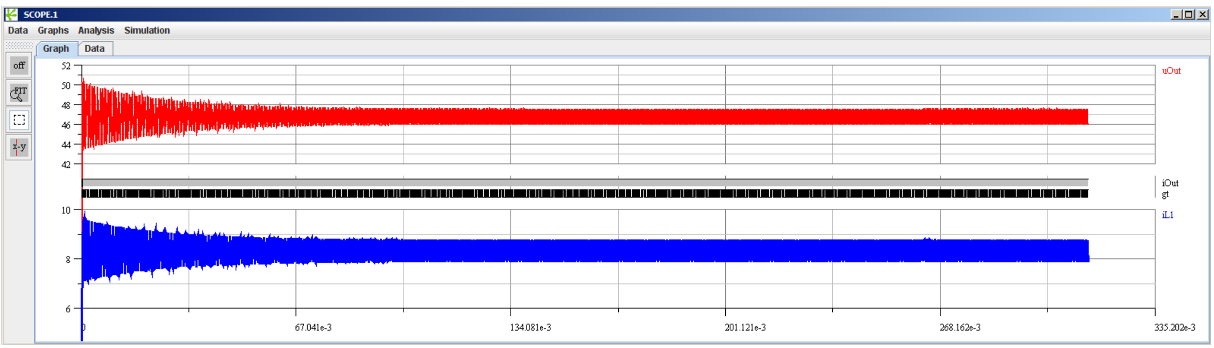


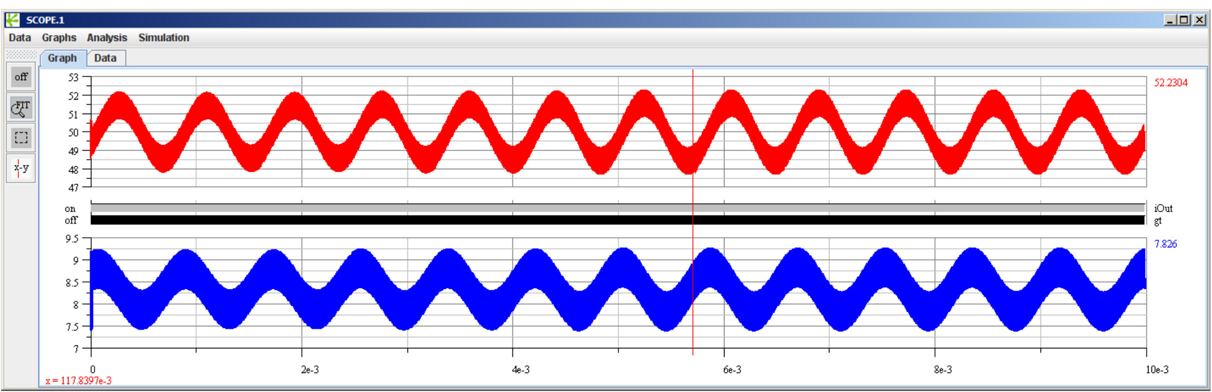
Save the Buck-Converter model from task A, *„buck.ipes"*, into a file with the name *"boost.ipes"* and modify the circuit corresponding to the boost converter figure above. Use the component values as given in the figure. For the exercise parts 1 to 3, you can assume that the boost converter operates in the continuous conduction mode.

1. Calculate the duty ratio *D*, so that the output voltage becomes U_{aus} = 50 V at steady-state. Insert your result into the simulation, and set the initial conditions of the energy storage components to the correct steady state values.

2. How long does the simulation need to reach steady state? Which loss components does the circuit contain? Play with the parameter values of the diode and the switch. Try to determine the long-term ringing frequency at the simulation start. Do you have an idea on how to calculate this frequency? (*Hint*: Consider a resonant circuit together with the step-up ratio of the converter)

1, 2: From the relationship $\frac{U_{aus}}{U_{DC}} = \frac{1}{1-D}$ *it follows that* $D = 1 - \frac{U_{DC}}{U_{aus}} = 0.76$ *. We can calculate the initial value of the inductor current as* $I_{L0} = \frac{I_{Last}}{1-D} = 8.333\,A$*. The circuit does not contain large power loss sources, therefore the initial ringing would never decay! If you have a look at the diodes and the IGBT switch you will recognize a forward voltage drop* U_f *and.* U_{DS_on} *, which is introducing some damping to the circuit. The following figures show* u_{Out} *and* i_L *(with a zoom factor on the time scale). Here, you can see the decay of the initial ringing, the period of the ringing as well as the current ripple.*



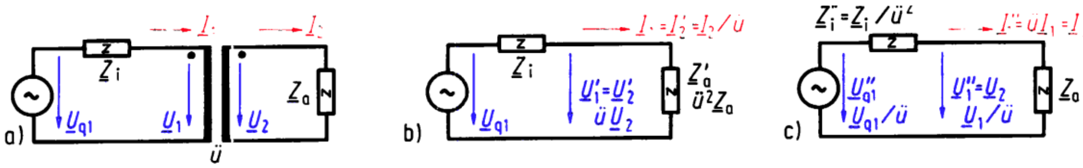


According to the forward voltage drops and the on-resistances oft he components, we can also observe a deviation of the output voltage mean value from the targeted 50 V.

The ringing frequency can be read from the plots to

$$f = \frac{1}{T} = \frac{Anzahl\ Schwinungen}{T_{ges}} = \frac{12}{1msec} = 1200Hz.$$

The circuit is building a resonant circuit (L and C), where we can regard the capacitor as being on the right-hand side of a transformer, which can be transformed to an equivalent capacitor on the primary side:



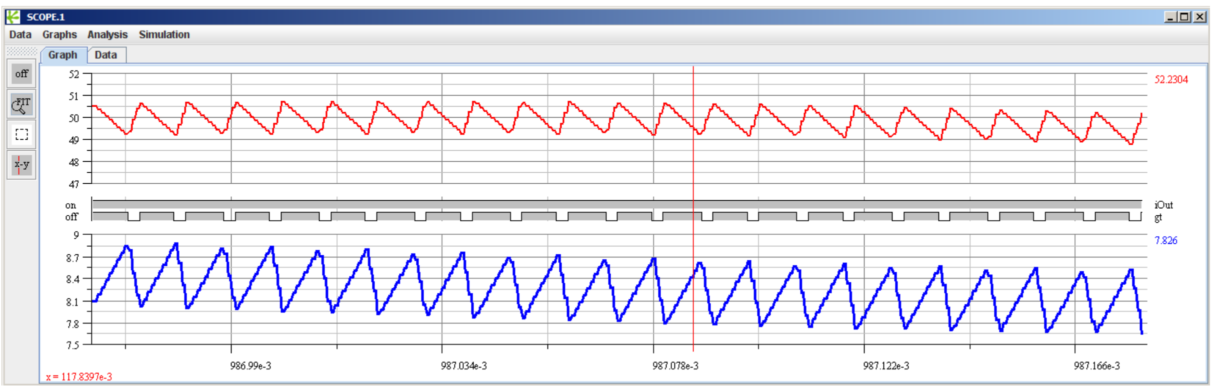
3.149 **Vollständige Schaltung (a) des idealen Übertragers sowie Ersatzschaltungen mit auf die Primärseite (b) bzw. Sekundärseite (c) umgerechneten Kenngrößen**

$$f = \frac{1}{2\pi\sqrt{LC`}} = \frac{1}{2\pi\sqrt{LC`}} = \frac{1}{2\pi\sqrt{LC\ddot{u}^2}} = \frac{U_{in}/U_{out}}{2\pi\sqrt{LC}}\ mit\ \ddot{u} = \frac{U_{out}}{U_{in}} = 0{,}24$$

Inserting numeric values, we get

$$f = \frac{12V/50V}{2\pi\sqrt{100\mu H \cdot 10\mu F}} = 1207\ Hz.$$

Zooming into the simulation results, we can observe the 100 kHz voltage- and current ripple of the circuit:



3. Calculate the output capacitor value C_{out} , so that the output voltage ripple is limited to a maximum of u_{aus} = 500 mV (peak-to-peak).

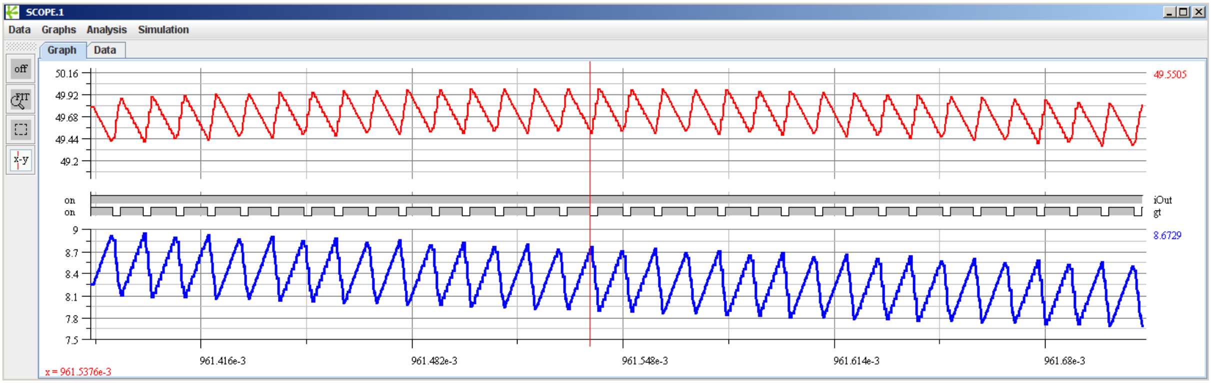
The maximum change of charge calculates as

$$\Delta Q = \frac{D \cdot i_{Last}}{f_S} = 15.2\mu C.$$

Hence, the minimum size of the capacitor is:

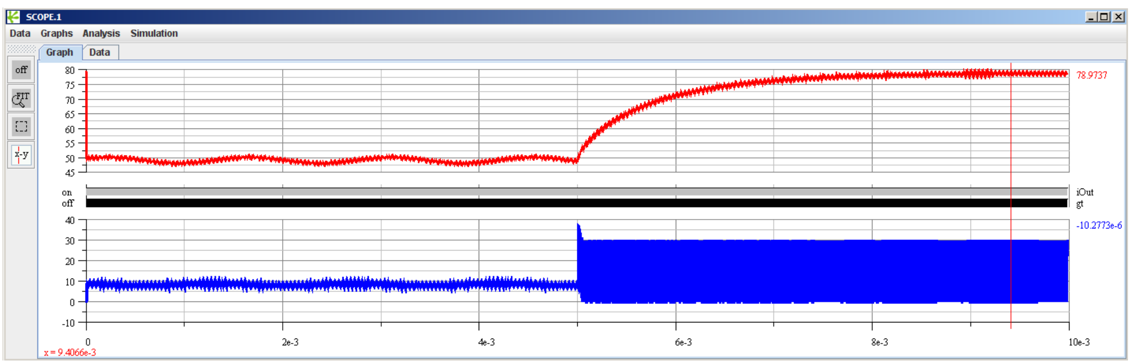
$$C_{aus} = \frac{\Delta Q}{\Delta u_{aus}} = 30.4\mu F.$$

Therefore, we get the results for the ripple current and voltage:

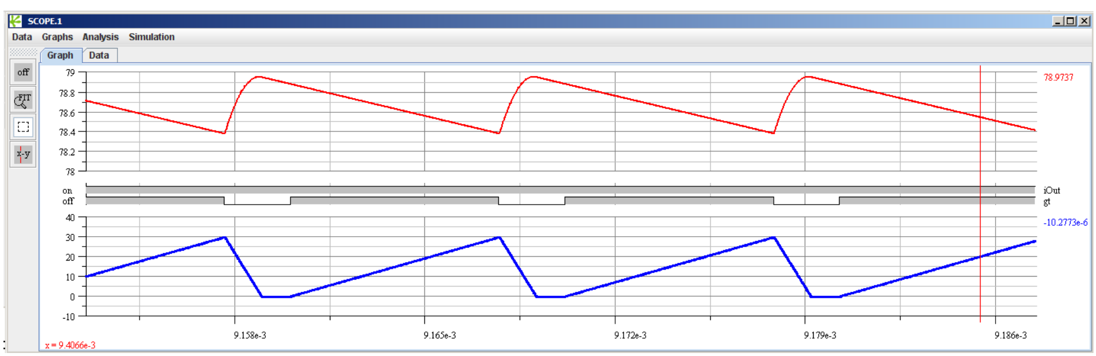


4. Now, please reduce the inductance value to *L* = 3 H. What happens to the output voltage? Please interpret your results. How long does the converter need to reach steady state?

   Since the converter is going to discontinuous conduction mode, the output voltage increases to approximately 79 V:



Zooming into the figure, we can observe the discontinuous current in the inductor:



Furthermore, the time to reach steady state is reduced when the converter operates in discontinuous conduction model. This can be explained – similar to the exercise part A, buck converter – due to the suppression of a free ringing in discontinuous conduction.

5. Which value do you have to select now for the duty ratio D to reach the required voltage of u_{out} = 50V?

In the discontinuous conduction mode, the duty ratio for the boost converter is calculated as

$$D = \sqrt{\frac{4}{27} \cdot \left(\frac{U_{aus}}{U_{DC}} - 1\right) \frac{I_{Load}}{I_{Lload\_limit\_max}}}$$

Here, $I_{Load\_limit\_max}$ *is the maximum current at the limit between continuous and discontinuous conduction mode:*

$$I_{Load\_limit\_max} = \frac{2}{27} \frac{U_{aus}}{L} T_S = 12.346\ A.$$

Hence, we get D = 0.563.