Power Factor Correction (PFC)

Exercise including solution

Exercise A: Simple Diode Rectifier

Figure 1 shows a simple diode rectifier, the output load is an ideal voltage source. In practice, at the DC side a huge capacitor is usually smoothing the output voltage, so that the constant output voltage in our model is a good approximation to reality.

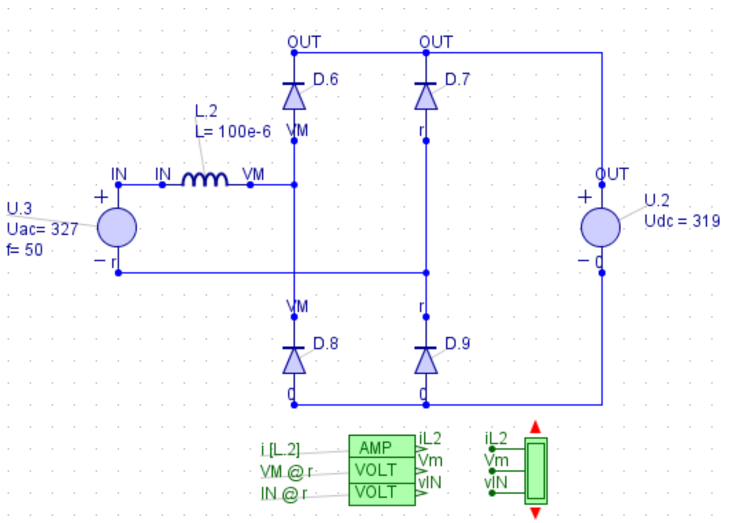


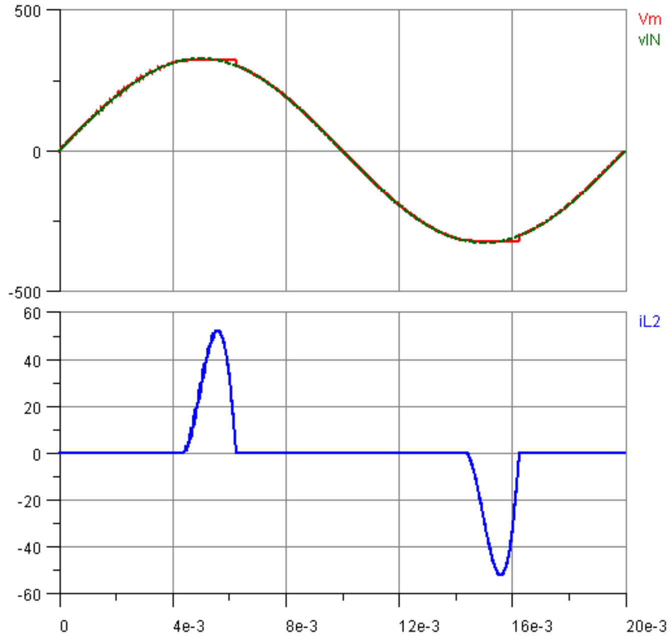
Fig.1

Implement the simulation model as shown in figure 1 in GeckoCIRCUITS, and use the component values as shown in the figure. Please consider that your simulation results will be dependent on the component values of the diodes. Use the standard diode settings in GeckoCIRCUITS, i.e. a forward voltage drop of 0.6V. Visualize the following simulation results within the GeckoCIRCUITS scope: input voltage u_{IN}, inductor current i_L and the diode bridge voltage u_m.

Comment: *Depending on the settings of the diodes forward voltage drops or conduction resistances,you will get slightly differing results in comparison to this solution. The values as shown in this document are obtained by using a forward voltage drop of 0.6V in the diodes, as set per default from the circuit simulator.*

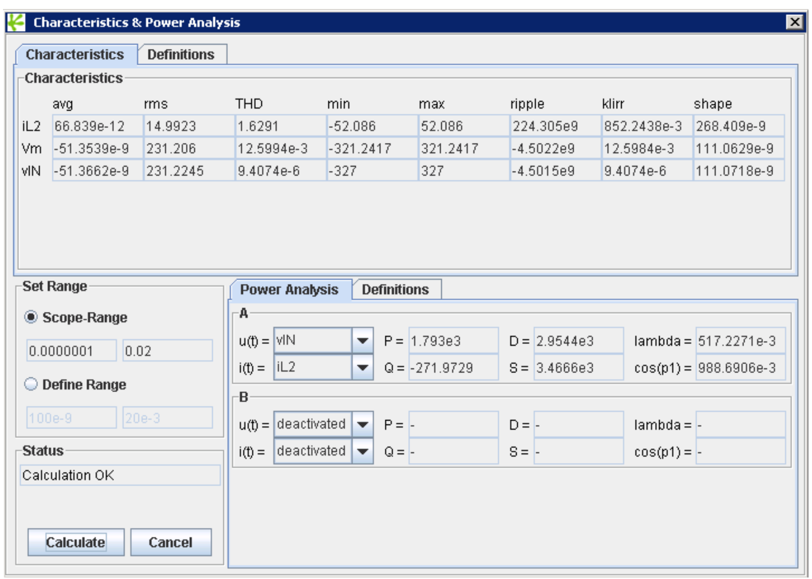
1. Set the simulation duration to 0.02 sec (a mains period) and select a reasonable value for the simulation step width d*t*. Use the built-in analysis tool of the GeckoCIRCUITS scope to calculate the mean value of the input active power. Which maximum input current i_L do you see at the inductor? Compare the simulation result with the theoretically calculated inductor maximum current, assuming a purely sinusoidal input current.

   The results can be seen in the following figures:



Mains voltage (green) and input voltage of the diode rectifier (red).
Lower plot (blue): Inductor current i_{L2}.

Power calculation – THD:



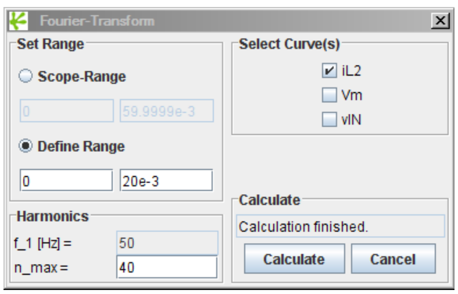
The mean output power is P=1793W. Assuming a sinusoidal input current, the maximum value of the inductor currents would be

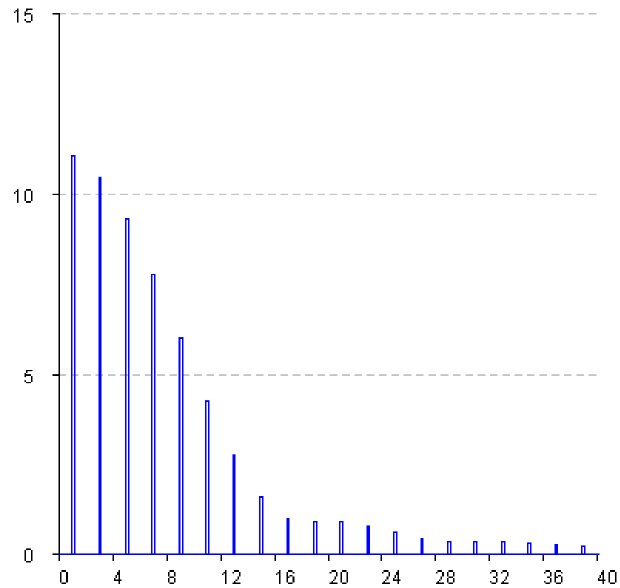
$$I_{Spk} = \frac{2 * P_{avg}}{U_{Spk}} \approx 11\ A$$

In our case with the diode bridge, however, the maximum current is 52 A.

2. Which harmonics does the input current contain? You can use the Fourier analysis tool of GeckoCIRCUITS to visualize the input current harmonics. Visualize the current spectrum up to the 40th harmonic.

   Besides the fundamental frequency (50Hz), we can also see odd-numbered higher order harmonics (150Hz, 250Hz, ...) in the input current spectrum. The following figure shows the Fourier calculation of the input current up to the 40th harmonic current:





3. Calculate the THD value of the input current (herefore, again, you can use the built-in analysis tool of the GeckoCIRCUITS scope).

   The THD value, which is defined as the ratio of the geometric sums of all harmonics tot he fundamental amplitude,

$$THD = \frac{1}{X_{(1),\mathrm{RMS}}} \sqrt{\sum_{k=2}^{\infty} X^2_{(k),\mathrm{RMS}}}$$

   is here calculated as THD = 163%

As you can see from your results, the simple diode rectifier feeds back harmonic distortions into the mains. In the following exercise part, we will discuss two simple topologies including a Power Factor Correction (PFC), which will significantly improve the THD.

Exercise B: PFC with a fixed tolerance bandwidth

Implement the simulation model of the rectifier according to figure 2, which includes a boost converter at its output. Please use the component values as given in the figure. Save the simulation model with a different name, e.g. *pfc_1.ipes*. Pay attention to the direction of the current flow within L_3, as the current measurement has to have the correct sign. You can enable the current direction visualization (pink arrows) in the menu "View->Flow-Direction".

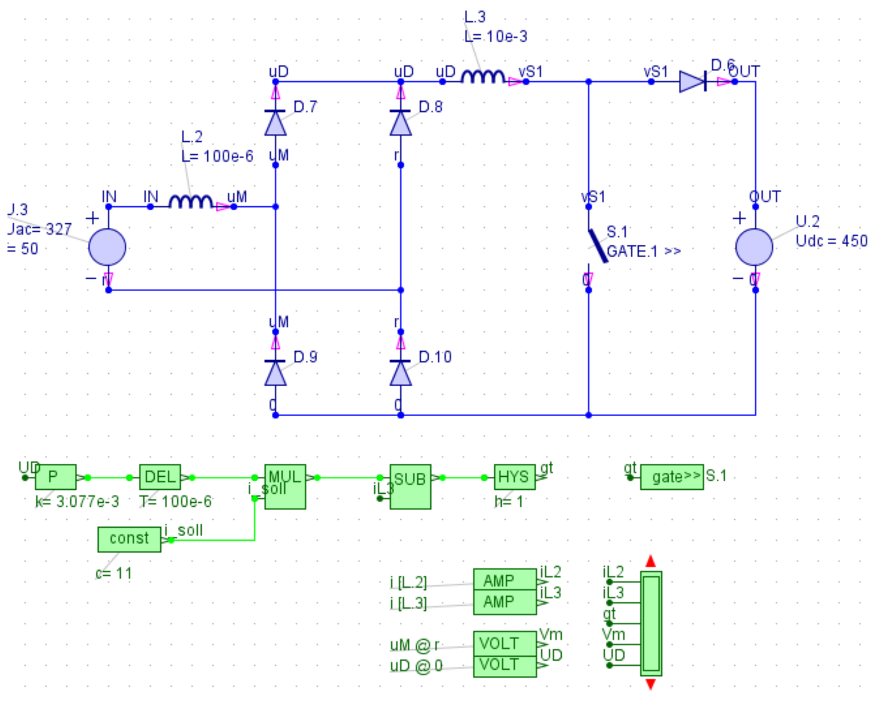


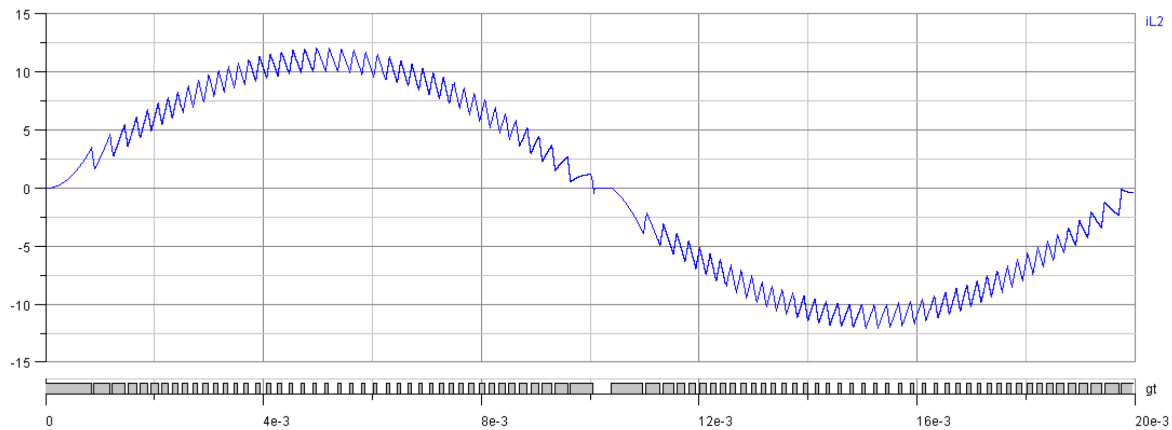
Fig. 2

Additionally to the values from exercise A, visualize the following circuit parameters: Voltage u_D and the inductor current i_{L3}. The boost converter that is used for the power factor correction is built by the inductor L, an ideal switch S_1 and the diode D_6. The switch is controlled by the gate signal *gt*. If the gate signal is zero, the switch is open, otherwise it is closed. Here, in contrast to the simple diode rectifier, the output voltage has to be above the amplitude of the input AC voltage. Otherwise, the boost converter cannot operate properly.

The model in figure 2 includes a simple control of the inductor current. The tolerance band control works in the following way: The inductor current i_{L3} is subtracted from its target value i_{soll} (SUB-Block in the control model) and the difference is then fed through to the input of a hysteresis block which controls the gate signal *gt*. The calculation of the reference value is done via multiplication of the normalized (and rectified) input voltage u_D with the desired input amplitude of the mains current.

4. Select the target value of the mains current to a value i_{soll} so that the mean active power of the rectifier corresponds to the value from exercise A.

   The input current amplitude – assuming a sinusoidal input current – was already calculated earlier as I_S=11 A. In the following figure, the simulation results of the PFC input current with fixed tolerance bandwidth is shown.



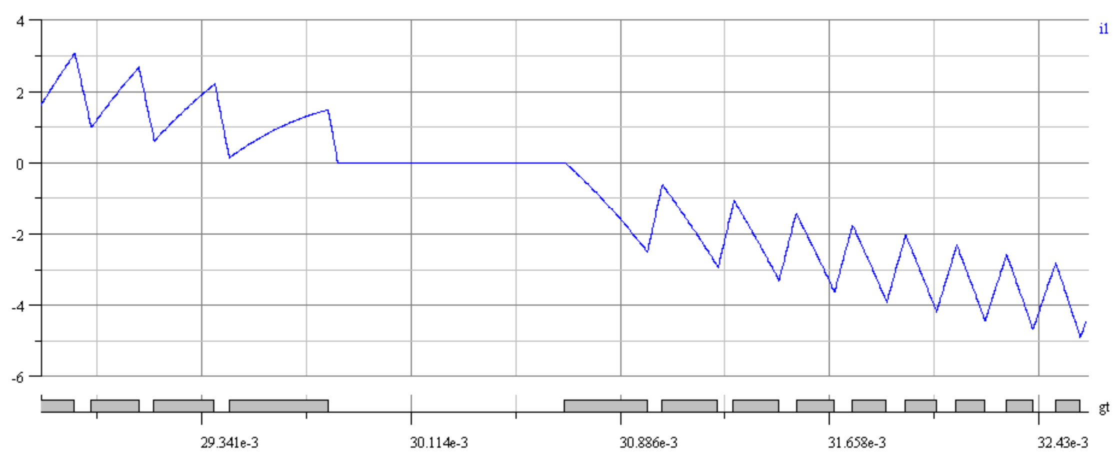
5. Try to play with the component parameters. Can you find a correlation between the tolerance band width and the switching frequency of the control?

   The (mean) switching frequency f_S is increasing with decreasing inductance or decreasing tolerance bandwidth (c is an arbitrary selected proportional constant):

$$f_S := c \cdot \frac{1}{L \cdot \Delta i_{Regler}}$$

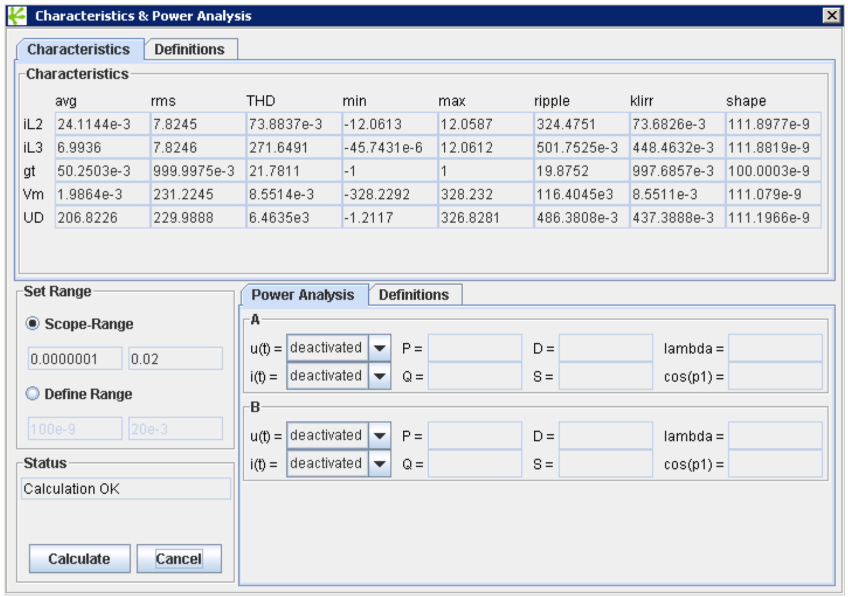
6. Have a look at the mains current close to its zero crossing. What do you observe?

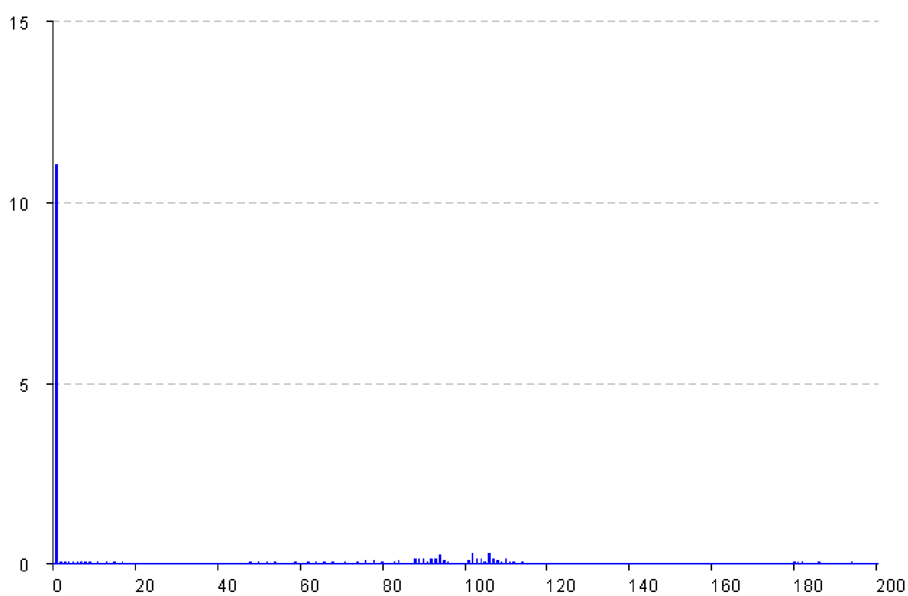
   Close to the current zero crossing, we can observe a deviation of the input current from the ideal value. The reason is that the input voltage of the boost converter is very small, here. The boost converter does not work properly in this operating range, since the switching frequency (given by the tolerance bandwidth) does not allow to follow the ideal current shape in this case.



7. Now, please re-set the output inductor value to 10 mH, and visualize the mains current spectrum up to 10 kHz via the Fourier analysis tool of the scope. Which harmonics do you observe? Calculate also the THD value and compare it to the THD value obtained for exercise A.

*In comparison to the simple diode rectifier, the harmonics of the current spectrum are strongly decreased. With a tolerance bandwidth of +/-1 A and an inductance of 10 mH, we can only see some small amplitude current harmonics at the frequencies around in the range of 5 kHz (50 Hz*100). Therefore, we get a tremendous improvement of the THD value of about 7.4 % in comparison to the diode rectifier.*





Exercise C: PFC with current proportional tolerance band

Another possibility for controlling the PFC is to vary the tolerance bandwidth proportional to the amplitude of the mains current. In this case, the current i_d should vary between $(1-k) \cdot i_{soll}$ and $(1+k) \cdot i_{soll}$, where i_{soll} is the current target value and k a constant in the interval $0 < k < 1$. You can find the corresponding simulation model in figure 3. Implement this simulation model in GeckoCIRCUITS, and use the given component values. Save your model with the file name *pfc_2.ipes*.

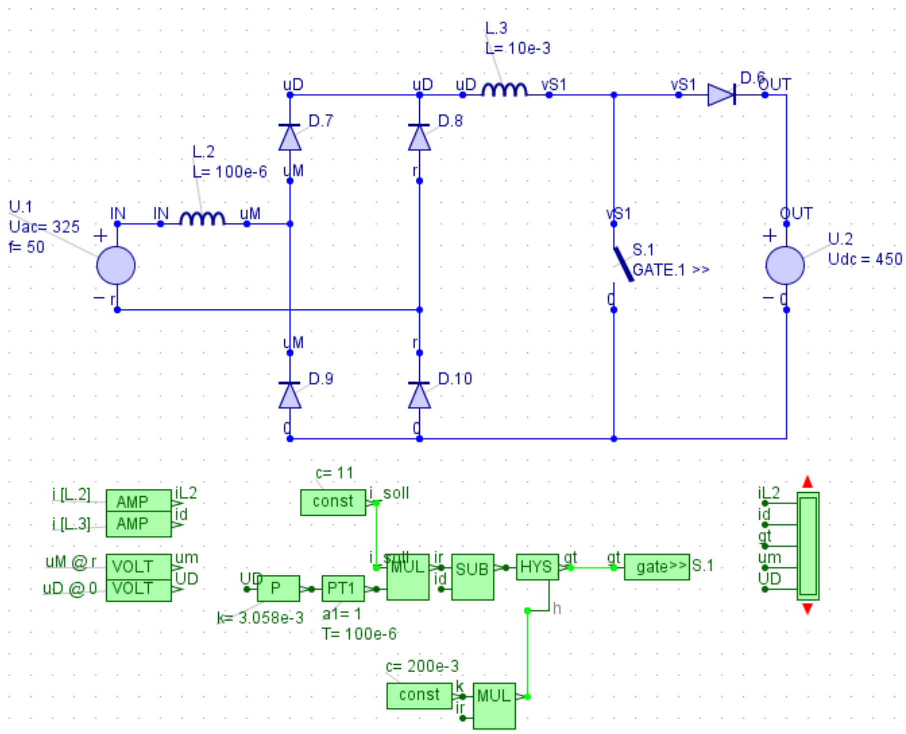
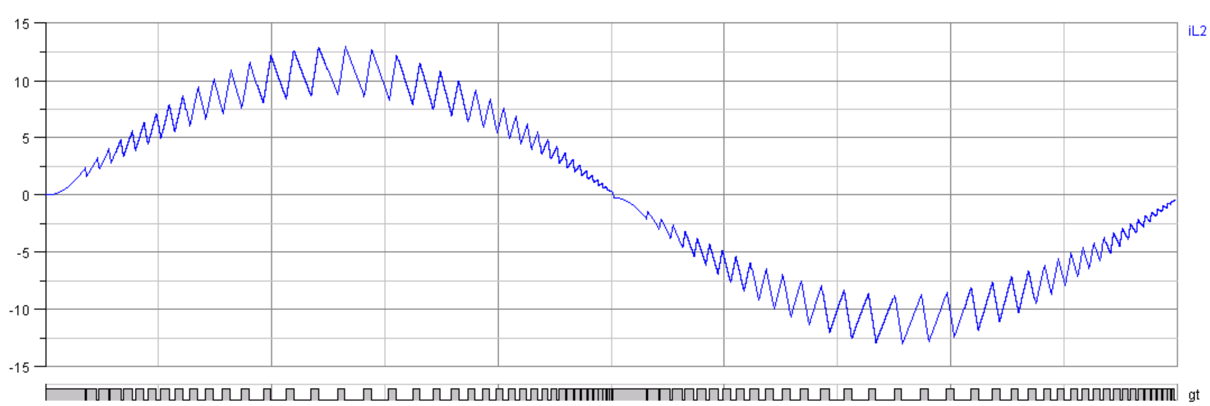


Abb.3

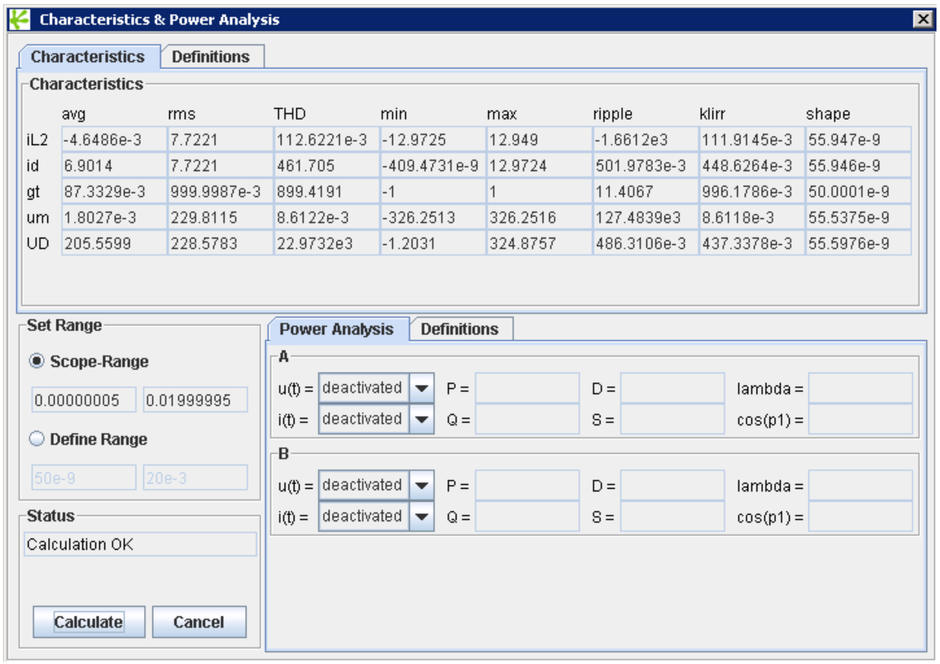
8. Set the target current value i_{soll} to the value from exercise part B. Please compare the current and voltage shapes as well as the mean switching frequency to the values from the previous exercise.

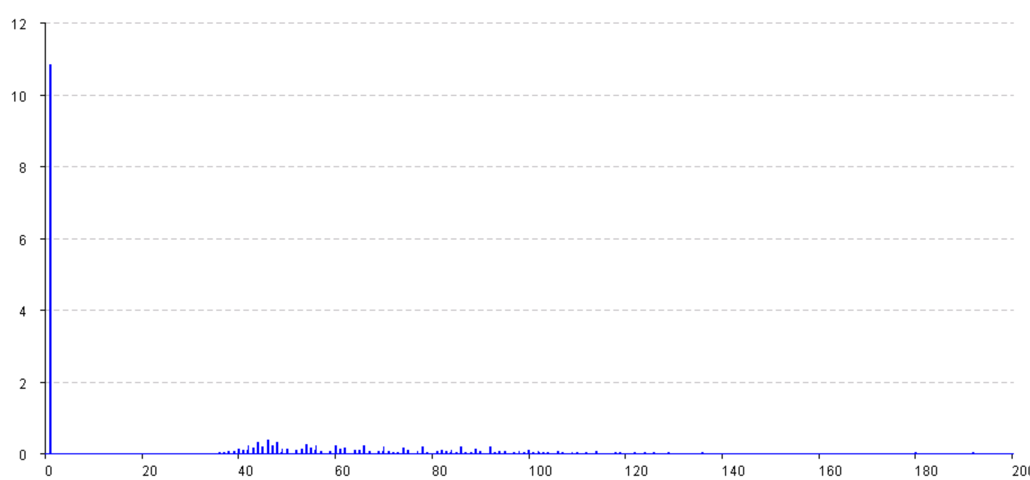
The shape of the input current during the zero crossing is improved significantly, since - for small input current values – the switching frequency increases:



9. Visualize the mains current i_{L2} harmonics spectrum. How big is the THD?

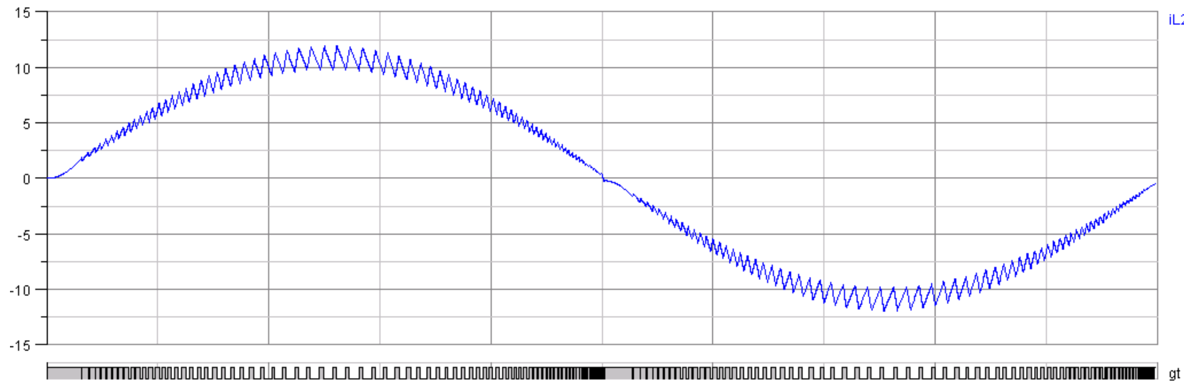
We can clearly recognize harmonics in the frequency range between 4 kHz to 6 kHz, the THD value is 11.3 % (using L = 10 mH and k = 0.2).

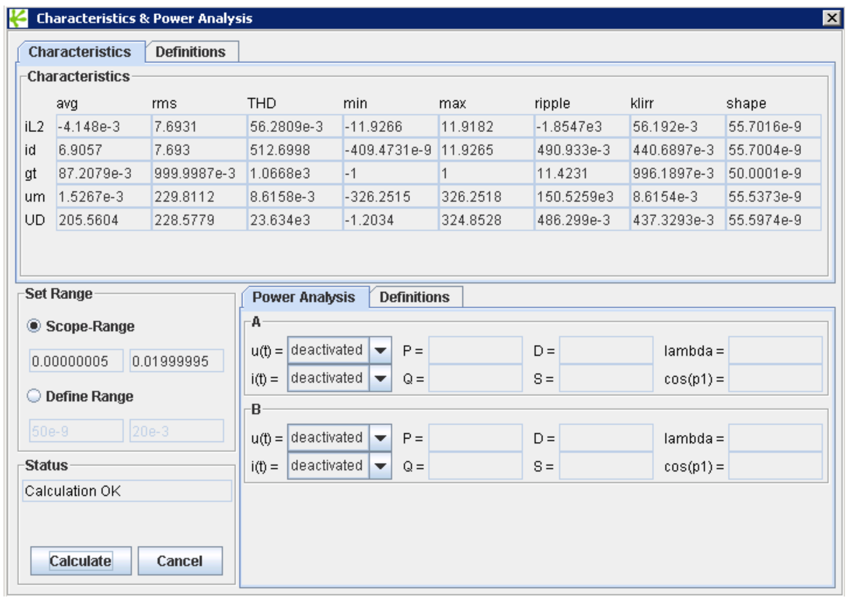




10. Which influence does the tolerance bandwidth constant k have on the harmonics and the switching frequency?

Decreasing the factor k results in a higher switching frequency as well as an improved THD value (and therefore less high-frequency current harmonics). The following figures are simulated with k = 0.1 :





	avg	rms	THD	min	max	ripple	klirr	shape
iL2	-4.148e-3	7.6931	56.2809e-3	-11.9266	11.9182	-1.8547e3	56.192e-3	55.7016e-9
id	6.9057	7.693	512.6998	-409.4731e-9	11.9265	490.933e-3	440.6897e-3	55.7004e-9
gt	87.2079e-3	999.9987e-3	1.0668e3	-1	1	11.4231	996.1897e-3	50.0001e-9
um	1.5267e-3	229.8112	8.6158e-3	-326.2515	326.2518	150.5259e3	8.6154e-3	55.5373e-9
UD	205.5604	228.5779	23.634e3	-1.2034	324.8528	486.299e-3	437.3293e-3	55.5974e-9