# Exercise 6: Four-Quadrant Converter

The grid-side connection of a suburban train should allow the transfer of electrical energy in both directions. In order to meet this requirement a four-quadrant converter (4QC) is connected to the single-phase grid. The grid delivers a single-phase sinusoidal AC voltage $V_{\mathrm{AC}}$ with frequency $f$. The usage of two four-quadrant converters in parallel allows an appropriate power distribution onto the power semiconductors. The two four-quadrant converters are operated in interleaving mode to minimize the current ripple. The transformer is required to adjust the secondary voltage, to establish isolation between the two voltage sides and to provide an essential inductance. Figure 1 shows the structure of the considered power supply topology:

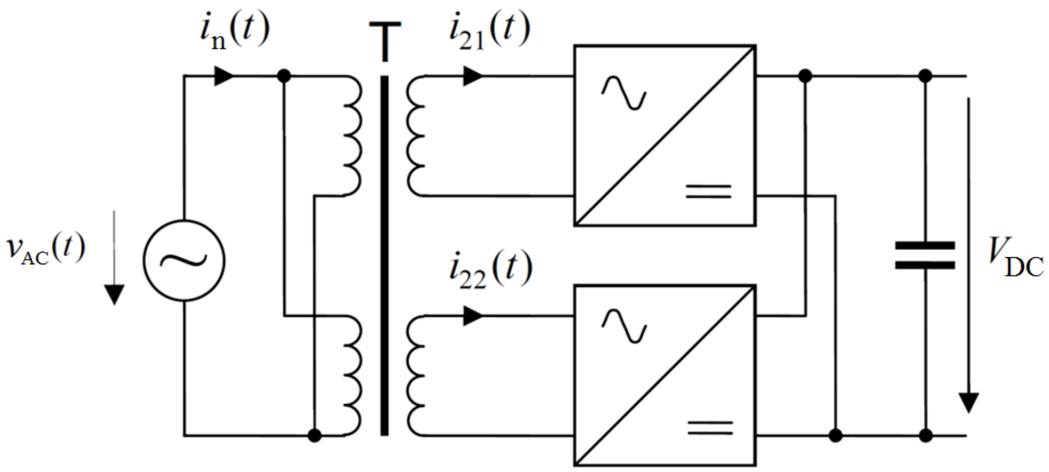


Figure 1: Power supply for a suburban train

The specification of the four-quadrant converter is given below:

| | | | |
|---|---|---|---|
| Nominal output voltage: | $V_{\mathrm{DC}} = 2.5\ \mathrm{kV}$ | Rel. short circuit voltage: | $u_{\mathrm{k}} = 20\%$ |
| Nominal output power: | $P_{\mathrm{N}} = 2\ \mathrm{MW}$ | Phase angle (grid side): | $\cos(\varphi) = 1$ |
| Grid voltage: | $V_{\mathrm{AC}} = 15\ \mathrm{kV} \pm 10\%$ | Switching frequency: | $f_{\mathrm{s}} = 300\ \mathrm{Hz}$ |
| Grid frequency: | $f = 16.667\ \mathrm{Hz}$ | Interlocking time: | $\tau_{\mathrm{s}} = 5\ \mathrm{\mu s}$ |

1. Draw the circuit diagram of a four-quadrant converter and explain its operating principle.
2. Draw qualitatively the control sequence of the semiconductor switches of two parallel four-quadrant converters for interleaved operation mode (phase shifted by 180 degrees). Draw the resulting output voltage (transformer secondary side) of the four-quadrant converters over ten switching periods.
3. Calculate the leakage inductances of the transformer. Assume that there exists only a secondary leakage inductance and that the apparent power of the transformer is 2 MVA.

4. The two four-quadrant converters should be controlled that way that only active power is drawn from the grid (target power factor mode). Determine the phase angles that are required as reference values for the controller driving the gates of the semiconductor switches for the two cases: rated load at nominal input voltage and half of rated load at minimum input voltage.
5. Calculate the ratio of the transformer considering the leakage inductance and the voltage fluctuation range.
6. How large is the actual required apparent power of the transformer?
7. How large is the maximum current ripple at nominal operation (rated current flow)?
8. Calculate the peak current and the peak voltage which can be seen as a measure for the stress on the transistors and the diodes in the four-quadrant converter.
9. Considering non-ideal and delayed switching of the power semiconductors, interlocking times have to be implemented. How large is the resulting voltage error?
10. Draw the power $P_{\mathrm{DC}}$ emitted to the DC-Link over one fundamental period. Complete the graph with the active power drawn from the grid, the reactive power that has to be compensated by the converter and the apparent power of the transformer.

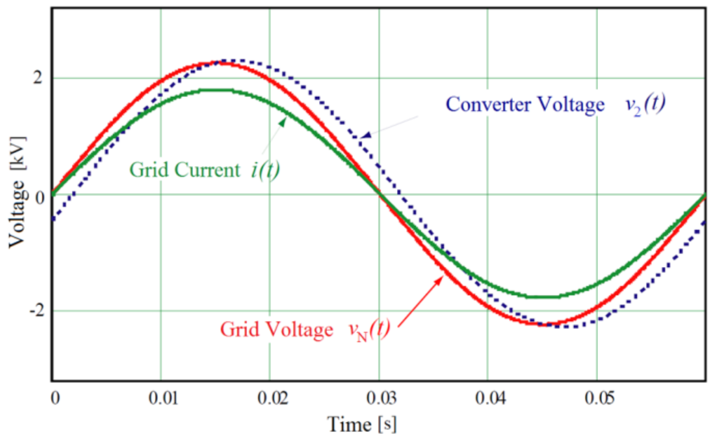


Figure 2: Voltages and currents transformed to the secondary side of the transformer

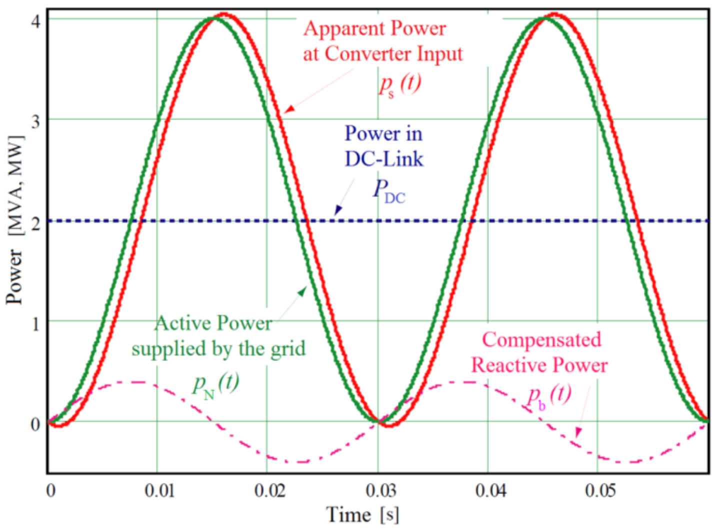


Figure 3: Solution to problem 10

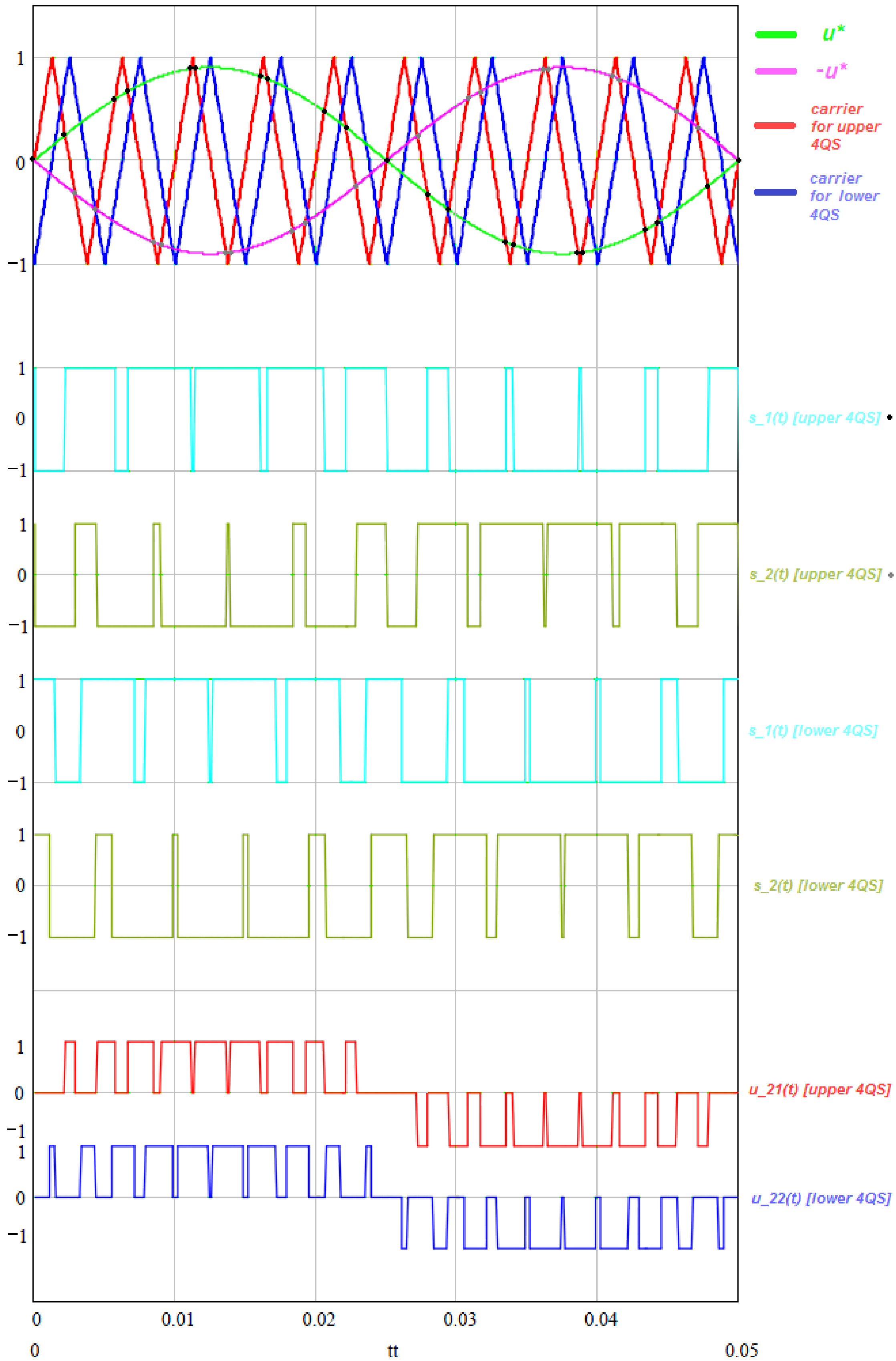


Figure 4: Solution to problem 2