

## Exercise 7: Control Design for Four-Quadrant Converter

The grid-side connection of a suburban train is achieved by a single phase four-quadrant converter (4QC). A simplified circuit diagram with input inductance, output capacitor and absorption circuit is shown in figure 1. The DC-link voltage will be controlled by a superimposed voltage controller with a subordinated current controller (cascaded control structure). Feeding electrical energy back to the grid should be possible.

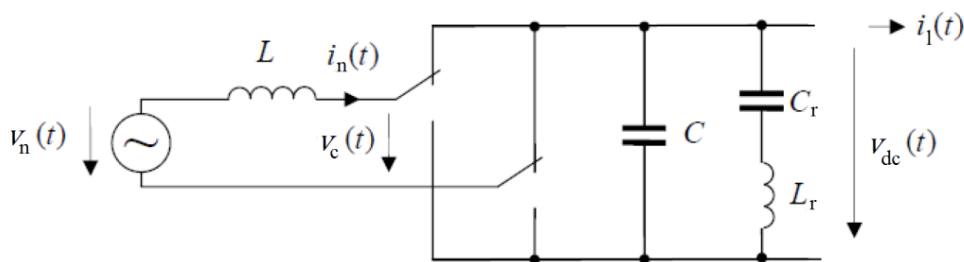


Figure 1: Four-quadrant converter with input inductance and output capacitor with absorption circuit in parallel

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

Nominal output voltage:	$V_{DC} = 2.5 \text{ kV}$	Resistance of inductance: $R = 0.01 \Omega$
Nominal output power:	$P_N = 2 \text{ MW}$	Phase angle (grid side): $\cos(\varphi) = 1$
Grid voltage:	$V_{AC} = 15 \text{ kV} \pm 10\%$	Switching frequency: $f_s = 300 \text{ Hz}$
Grid frequency:	$f = 16.667 \text{ Hz}$	

Adopt the values from *Exercise 06 – Four-Quadrant Converter*. In this exercise only one 4QC is considered. Download the provided and zipped file *Ex07\_4QC.rar*, extract it and copy the Simulink model and the initialization m-file to a new folder. Start MATLAB, open the Simulink model and initialize it.

1. Derive the average model of a four-quadrant converter with inductor  $L$  at the mains side and capacitor  $C$  at the DC-link side and implement the model in MATLAB/Simulink. Note that the inductor has a serial resistance. Assume that the capacitor is ideal.
2. At first replace the output capacitor by a constant voltage source. Implement a PWM-unit for interleaved switching mode and check the functional principle of your implemented 4QC by feeding the PWM with a sinusoidal reference voltage. The required phase can be obtained directly from the grid generator (sine block). Test different phase angles between reference voltage and grid voltage amplitudes. Check and evaluate the resulting grid currents.
3. Implement a feed-forward control for the stationary state according to the formula:  $v^* = \hat{v}_n \cdot \sin(\omega t) - \hat{i}_n \omega L \cdot \cos(\omega t)$ , with  $\hat{i}_n$  being the grid current amplitude. The phase angle  $\omega t$  can be again obtained from the grid generator. Test the stationary and dynamic behavior.

4. Add a P-controller to the current control and determine its gain. Check the behavior of the current controlled system.
5. Remove the constant voltage source in the 4QC model and replace it by the output capacitor. Consider also a load current. Complete the control structure by a superimposed voltage PI-controller. Design its parameters and test the controlled system without any load current at first.
6. Activate the load current to discharge the DC-link capacitor. Change the load current stepwise and study the behavior of the controlled system (for both power flow directions).
7. With increasing current the power oscillations with double grid frequency will occur more and more intensive in the DC-link voltage and also in the closed control loop. To overcome this problem an absorption circuit has to be added to compensate the double grid frequency. The resonant frequency of the filter has to be set to  $\omega_{r0} = 2\pi 2f = \frac{1}{\sqrt{L_r C_r}}$ . As a further condition in the design process the voltage of the capacitor at rated load must not reverse due to the fact that an electrolyte capacitor should be used.  
Suggestion for calculation: Determine the amplitude of the power oscillation from the apparent power. Then calculate the amplitude of the filter current with double grid frequency. The capacitor voltage  $v_{C_r}$  consists of this current amplitude and the value of the DC-link voltage.
8. Check the behavior of the controlled system and optimize the parameters of your controller.
9. Current limitation: During dynamic transition states currents could exceed a maximum allowed value and in consequence burden the power electronic devices in an unacceptable way. Assume that a temporary current of 120% of the rated current is acceptable. Modify your control structure by inserting a saturation block in the reference-current-path. At which position has this block exactly to be inserted (instantaneous reference current or amplitude value of the reference current)? Discuss advantages and disadvantages of both insertion positions.
10. As long as the current limitation is active the integral part of the PI-controller must not integrate the control error any further. Instead the integral output must be held at its least position when the saturation was inactive. Add a so called anti-reset-windup structure (ARW) to the voltage controller and study its behavior with and without an ARW-method by applying large dynamic load steps.