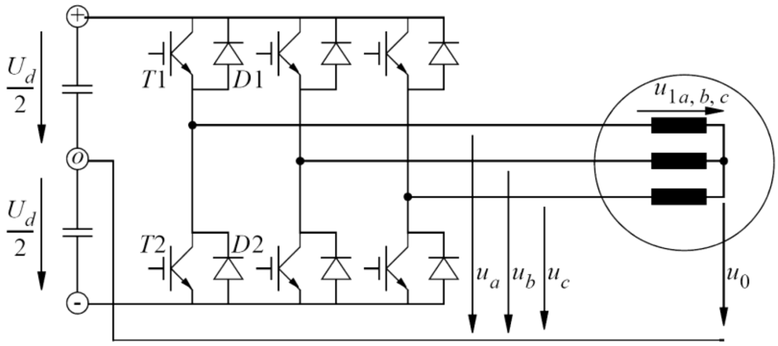
A Simple Three-Phase Inverter Model (including Solution)

Introduction

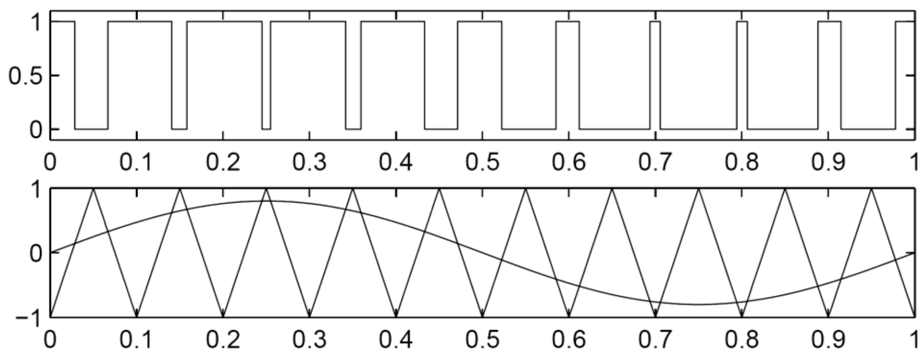
We will build a simple model of the tree-phase inverter, as given in the figure below. Such a converter is in practice only a part of a complex power electronic system. For instance, in traction applications, the DC side is usually connected via a rectifier to the mains. Additionally, the control of the switches will be modeled in this exercise. The exercise if focusing on the modulator which controls the bridge legs via the "undershoot operation". You will first build and test the modulator within GeckoCIRCUITS. Then, you connect the modulator with the power circuit, with the aim to analyze the behavior of the converter at different operating points.



The Modulator

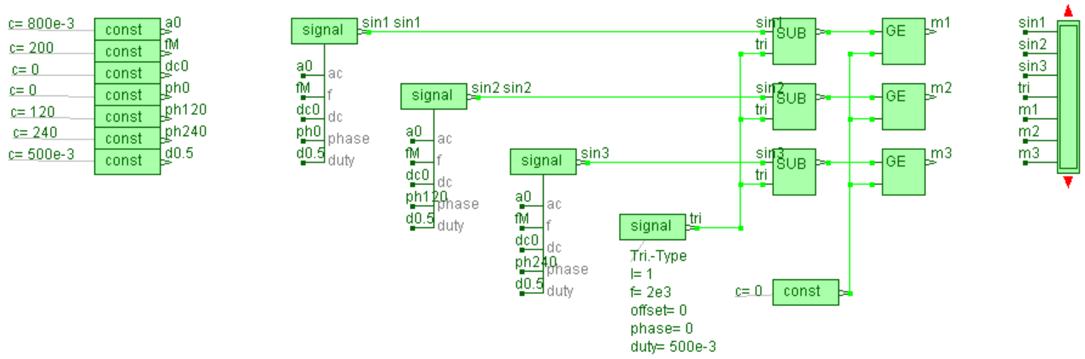
Each of the converter bridge legs switches a phase of the AC output side either onto the positive or negative DC input terminal. Hence, every bridge leg is a switch between two different circuit states. Mathematically, we can express this into a switching function S for each bridge leg phase a, b and c, which can have the two values 0 and 1: $S_a = \{ 0, 1 \}$ $S_b = \{ 0, 1 \}$ $S_c = \{ 0, 1 \}$.

For the modeling of the switching function, we use the so called „undershoot operation“. The modulator is using a voltage value to calculate a corresponding pulse width signal (PWM). We shortly discuss the principle of the undershoot operation:



As you can see in the figure above, the switching state is S = 1, when the sinusoidal control signal u_{St} is bigger than the triangular signal u_H , otherwise, $S = 0$.

Now, build the modulator with undershoot operation in GeckoCIRCUITS. The modulator should generate the three-phase switching pattern for the power switches, using phase-shifted sinusoidal input signals. You will need the following control blocks for building the modulator: “Signal Source”, “SUB” and “Greater Equal (GE)”.
To generate a control schematic that is not too cluttered, you can use labels instead of the green control wires. When to labels have the same name, they will behave as connected.



Sinusoidal signal generator:

- Use three „signal sources“ to get the tree-phase sinusoidal control signals. The signal sources should be phase-shifted with 120 degree, respectively.
- Set the modulation ration a_0 (amplitude of the sinusoidal control voltages) to $a_0 = 0.8$.
- The frequency should be set to u_{St} ist 200 Hz.

Triangular signal:

- You will get a triangular comparator signal, when you set the type of an additional signal source to „triangular“.
- Set the switching frequency of the triangular signal to $f = 2000$ Hz.

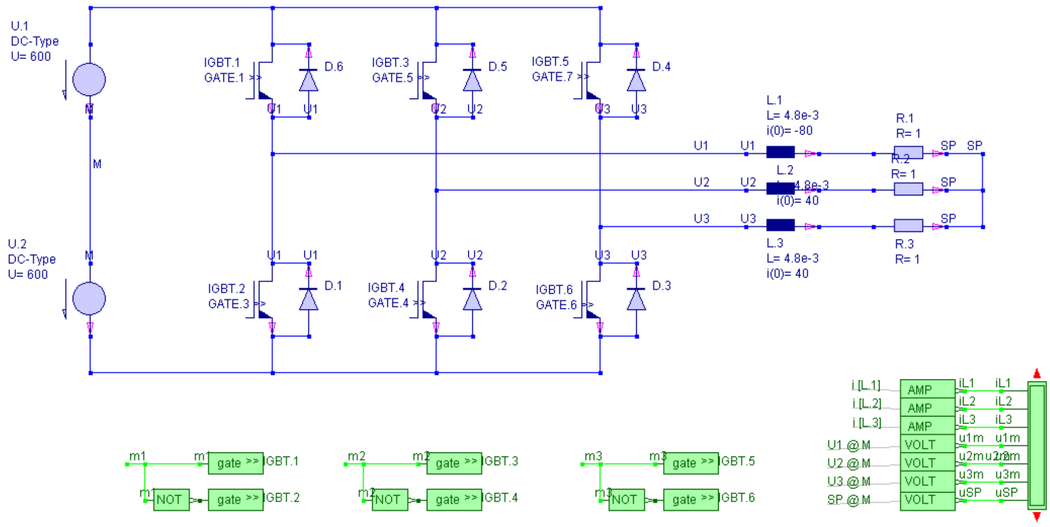
Comparator

- Using a subtraction block (SUB) and a comparison block (Greater Equal, GE) to produce the three control signals for the power circuit.
- The greater-equal block should work the following way: For input values larger than 0, the output value should be 1, otherwise, 0.

Now, please test your modulator by applying sinusoidal input values, and visualize the output signals together with the inputs in a GeckoCIRCUITS scope. Please also consider to change the simulator step-width dt to a smaller value, since the default value of dt = 1 µsec is not small enough.

Modeling of the Power Circuit

After finishing and testing the modulator, we will build the power circuit in GeckoCIRCUITS (see the figure below). Therefore, you will use the circuit components “IGBT”, “Diode”, “Inductor”, “Resistor” and “Voltage Source”. The inverter is connected to a three-phase *RL* load ($R = 1\ \Omega$, $L = 4.8$ mH).
The two switches within a bridge leg will be switched synchronously. Therefore, you can produce an inverted control signal to *m1*, *m2* and *m3* using the “NOT” signal blocks.
In reality, you would have to ensure that the DC voltage is not short-circuited over a bridge leg by introducing a delay between the two switches. However, we don’t include this into our model.

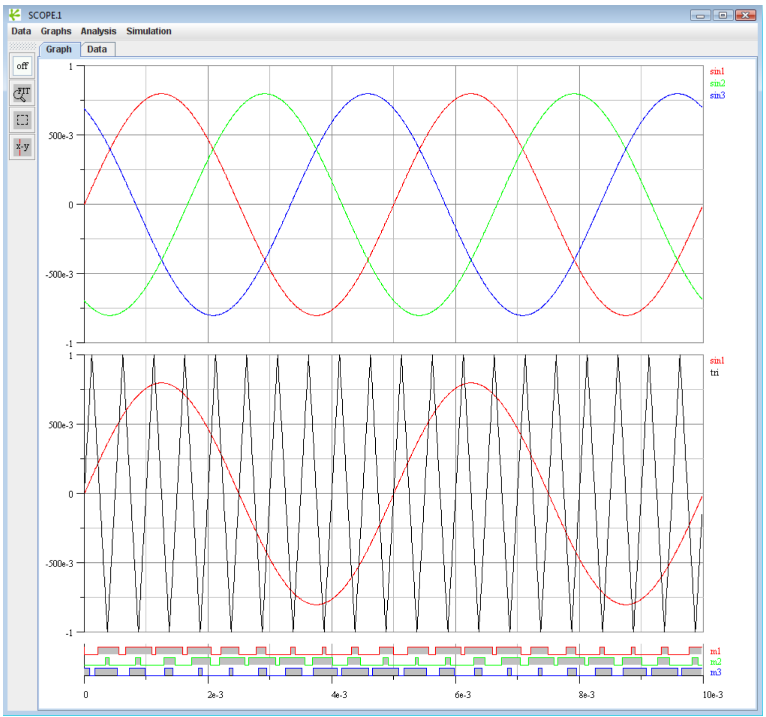


After finishing the power circuit model in GeckoCIRCUITS, please visualize the following circuit properties within the GeckoCIRCUITS scope: Phase currents, phase voltages, zero-voltage between the *RL* load star point and the midpoint of the DC input voltage.

As a reasonable simulation time, you could select for example *T* = 20 ms. Additionally, visualize the following space-vector properties using the space-vector plotter block from GeckoCIRCUITS: output voltage, mean-value of the output voltage (averaging time: one switching period) as well as the space vector of the load current.

To accelerate the time to reach steady-state, you can use reasonable initial values for the three inductor currents. Hereby, please consider that the three initial currents must add to zero – otherwise the solver might have a problem.

Visualization of the switching patterns:



Initial values oft he indcutors: With the sinusoidal signal for the modulation, at t = 0 we get a voltage space vector of

$$\underline{u} = a_0 \cdot 600V \cdot (-j)$$

Therefore, we can calculate the steady-state current space vector

$$\underline{i} = \frac{\underline{u}}{R + j \cdot \omega \cdot L} = \frac{-j \cdot a_0 \cdot 600V}{R + j \cdot \omega \cdot L} = (-77.4 - 12.8 \cdot j)A$$

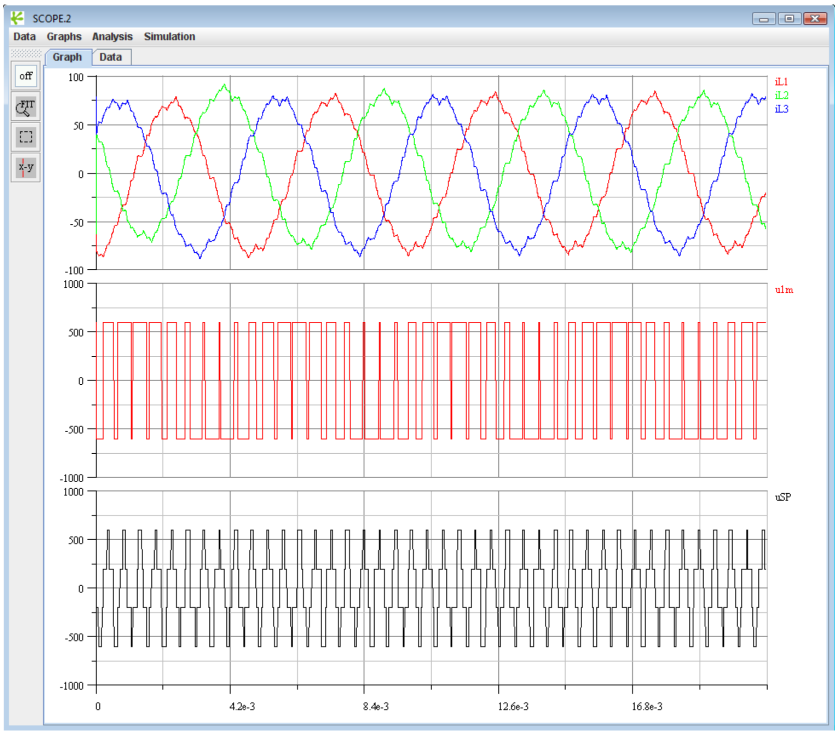
With the re-transformation into the three-phase system, we get:

$$i_a = i_\alpha = -77.4A$$

$$i_b = \frac{1}{2}\left(\sqrt{3}i_\beta - i_\alpha\right) = 27.6A$$

$$i_c = \frac{1}{2}\left(-\sqrt{3}i_\beta - i_\alpha\right) = 49.8A$$

You have especially to consider that the three values add to zero, otherwise the initial currents are set to a non-physical state. Finally, we get the following curves for the voltages and currents (without midpoint connection):



Simulation and Analysis

1. Start the simulation and look at the simulation results in the GeckoCIRCUITS scope. Which amplitude does the output voltage fundamental frequency have? You can use the Fourier analysis tool within the scope to calculate the fundamental amplitude.

   We can calculate the amplitude oft he voltage space vector to:

   $$|\underline{u}| = a_0 \cdot 600V = 480V$$

   The current space vector hast he amplitude

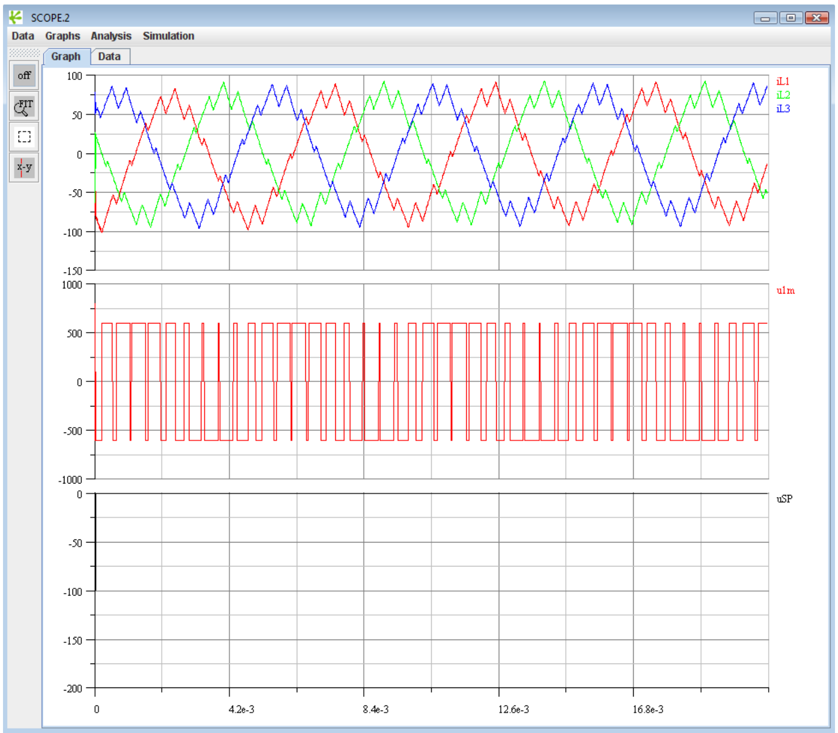
   $$|\underline{i}| = \left|\frac{\underline{u}}{R + j \cdot \omega \cdot L}\right| = 78.5A$$

The phase-shift between output voltage and output current is:

$$\varphi = \angle\left(\frac{\underline{u}}{\underline{i}}\right) = \angle(R + j \cdot \omega \cdot L) = arctan\left(\frac{\omega \cdot L}{R}\right) = 80.6°$$

2. Connect the midpoint of the input voltage and the star-point of the *RL* load. How do the converter output voltage and currents change, in comparison to the case without midpoint connection? How big is the current ripple in the inductors in both cases?

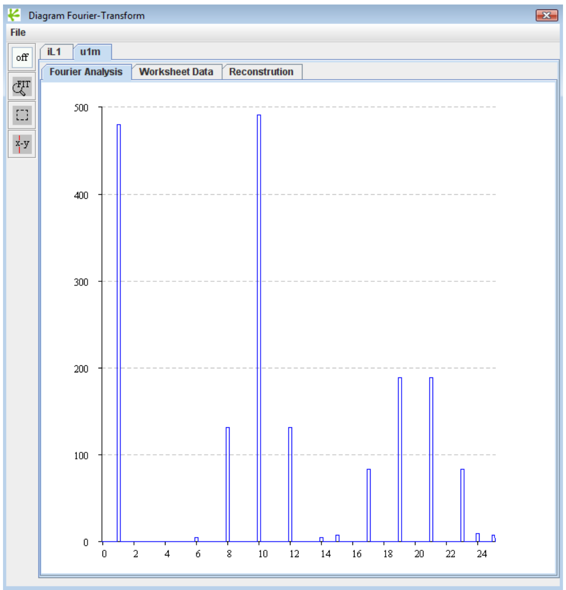
The amplitudes of the current and voltage fundamental frequency is Independent of the midpoint connection! Furthermore, the fundamental frequency phase shift does not change when the midpoint is connected. In comparison to exercise part 3, we can observe an increase in the current ripple.



Currents and voltages with midpoint connetion

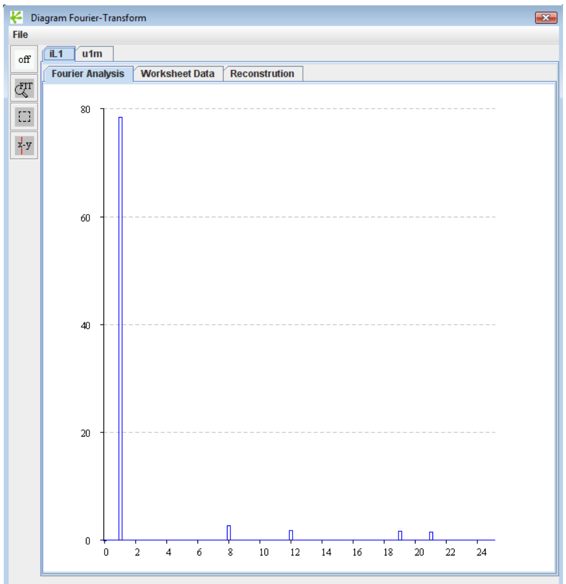
3. Use the Fourier analysis tool of the scope to visualize the spectrum of the output voltages and currents up to a frequency of 5000 Hz. Do this analysis for both cases: with and without midpoint connection.

We can read a fundamental frequency voltage amplitude of 480V from the Fourier analysis (200 Hz – ordinal number 1). A huge amplitude of the frequency component at 2 kHz is also clearly visible., as well as the side bands at 1600 Hz and 2400 Hz. These frequencies are obtained by a convolution between the mains frequency and the switching frequency.



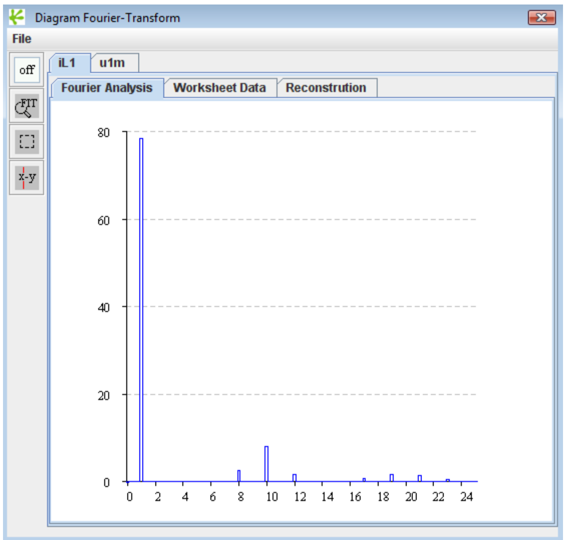
Voltage spectrum without midpoint connectiont

We can also observe in the spectrum that the current component at the triangular signal frequency (2 kHz) is NOT visible. However, the sidebands of the current spectrum are still visible.



Current spectrum without midpoint connection

Including the midpoint connection, the current harmonc at switching frequency does not vanish anymore, but is clearly visible. We can read the amplitude of this current at 2 kHz as 8 A.



Current spectrum including the midpoint connection

4. Vary the values of the switching frequency, modulation ratio and inductance values. Which influence on the current harmonics do you observe?

Increasing switching frequency: the current ripple reduces. A change of switching frequency does not influence the fundamental frequency amplitude oft he load current.

Modulation ratio: The amplitude of the load current fundamental frequency is changing proportional the the modulation ratio, the ripple is only changing marginally. (The ampltudes at 2 kHz decrease with increasing modulation ratio, whereas the side bands at 1.6 kHz and 2.4 kHz will increase with increasing modulation ratio.)

Input DC voltage: Increasing the input voltage has the same effect as the decreasing modulation index, and vice versa.

Inductanc values: By changing the inductance values, the time constants of the output filter alter (Lowpass). Higher inductance values decrease the current ripple, however the cut-off frequency of the filter is shifted to smaller values, which has an effect onto the fundamental frequency of the signal.