Experiments Using Electronics Workbench

Objective

Procedure. The practice includes a set of exercises in power electronics meant for Multisim from Electronics Workbench software. The exercises tasks are:

- development and calculation of power electronics circuits,
- selection of electronic components,
- schematic building,
- voltages and currents measuring,
- voltage and current waveforms analyzing,
- explanation and documentation of the results.

At the end of each exercise, compare calculated and experimental data. A report should include:

- experimental circuit diagram,
- resulting and comparative data tables,
- voltage and current traces with indication of axes scales,
- dependencies diagrams,
- conclusions with result explanation.

Required Components and Instruments

- Sources: ground, dc voltage source, ac current source, voltage-controlled voltage source, current-controlled voltage source, pulse voltage source, and clock source.
- Basic: resistor and potentiometer, capacitor, inductor and variable inductor, switch and voltage-controlled switch.
- Diodes: diode, full-wave bridge rectifier, silicon-controlled rectifier (SCR).
- Transistor: 3-terminal enhancement n-MOSFET.
- Analog IC: 3-terminal opamp.
- Indicators: voltmeter, ammeter.
- Miscellaneous: buck converter, boost converter, buck-boost converter.
- Instruments: oscilloscope, function generator.

Reference Data

- Load power $P_d = 10 \text{ W} \text{ to } 100 \text{ kW}$.
- Load resistance $R_d = 1 \Omega \text{ to } 100 \text{ k} \Omega$.
- Supply frequency $f = 50 \text{ Hz}$. 
1. Single-Phase Half-Wave Rectifiers

Exercise 1.1. Simple M1 rectifier

1. To begin with, draw and build the schematic using the only 4 components: the ac voltage source, a diode, a resistor, and the ground:
   - connect the positive pin of the voltage source to the diode anode and ground its negative pin,
   - then connect the load between the diode cathode and ground.

2. Add an oscilloscope and connect it to view the load voltage \( U_d \).

3. Activate the circuit simulation and view result. Tune the oscilloscope settings either before or during simulation.

4. To view the load current, add the current-controlled voltage source in series with the load resistor and connect it to the oscilloscope. Tune the oscilloscope and view both signals: the load voltage and the current.

Exercise 1.2. M1 rectifier with resistive load

1. Calculate the required average load voltage \( U_d \) and load current \( I_d \) using the Ohm’s law.

2. Calculate the required rms supply voltage as follows:
   \[ U_s = \pi U_d / \sqrt{2} \]

3. Calculate the peak inverse voltage, \( PIV \) (also called reverse breakdown voltage, \( BV \)) of the diode as follows:
   \[ PIV = \pi U_d \]

4. In the circuit of Exercise 1.1, assign values \( U_s, f, R_d \) and select the diode model from the library.

5. To measure average voltage \( U_d \) and current \( I_d \), add a dc voltmeter across the load and a dc ammeter in series with the load. Also, connect the oscilloscope to view the load voltage \( U_d \).

6. To view the diode inverse voltage, add the voltage-controlled voltage source across the diode and connect it to the other channel of the oscilloscope.

7. After activating the circuit, tune the oscilloscope and view both signals: load voltage and diode inverse voltage.

Exercise 1.3. M1 rectifier with LC filter

1. In the circuit of Exercise 1.2, measure the peak-to-peak ripple voltage \( U_r \) and calculate the ripple factor of the output waveform as follows:
   \[ r = U_r / (2U_d) \]

2. Calculate the power factor of the circuit as follows:
   \[ \cos \phi = P_d / S = (2\sqrt{2}) / \pi^2 \]
3. To measure the power factor experimentally, add an ac ammeter in series with the diode and ac voltmeter across the ac voltage source. After activating the circuit, measure $U_s$, $I_s$, $U_d$, $I_d$, and calculate $\cos \phi$ with $S = U_s I_s$ and $P_d = U_d I_d$.

4. For tenfold lowering of the ripple factor ($r_C = r / 10$), add an LC filter built on a capacitor across the load resistor and a reactor in series with the diode and calculate filter parameters ($H \cdot \mu F$) as follows:

$$LC = 10 \cdot (r / r_C + 1)$$

5. After activating the circuit, measure $U_s$, $I_s$, $U_d$, $I_d$, and calculate the new value of the power factor. Measure the maximum $U_{d\text{max}}$ and minimum $U_{d\text{min}}$ rectified voltages and their average value $U_d$ and calculate the actual ripple and power factors as follows:

$$r_C = (U_{d\text{max}} - U_{d\text{min}}) / (2U_d), \quad \cos \phi = \frac{P_d}{S}.$$  

Exercise 1.4. M1 rectifier with inductive load

1. Build an M1 rectifier circuit with the ac voltage source, a diode, a resistor, and the ground. Place the oscillator and connect it to view the load voltage and load current. Also, add the indicators to measure the load voltage and current. Assign the reference values and select the diode model as in previous exercises.

2. Build an inductive load by adding an inductor $L = 50$ to $5000 \, mH$ to the load circuit.

3. After activating the circuit, view, explain, and document the result.

4. To compensate the inductance, add the same LC filter as in Exercise 1.3 and fine-tune the circuit.

Exercise 1.5. M1 thyristor rectifier

1. Build a schematic using an the ac voltage source, a thyristor (SCR), a resistor, the pulse voltage source, and the ground:

- connect the positive pin of the voltage source to the thyristor anode and ground its negative pin,
- then connect the load between the thyristor cathode and ground
- connect the pulse voltage source to the thyristor gate and ground it.

2. Place the oscillator and connect it to view the load voltage and current. Also, add the indicators to measure the load voltage and current.

3. Calculate the required rms supply voltage $U_s$ and assign the values of $U_s$, $f$, $R_d$ and the pulse voltage source's Period $T = 1 / f$.

4. After activating the circuit, view the signals. Use the pulse voltage source as a firing regulator by changing its Delay time. To reduce the firing angle, set delay near zero. To enlarge the angle, raise the delay up to $T / 2$.

5. Change the firing angle from 0 to 180 degrees, measure the load voltage, write it into a table, and build the control curve that is the diagram of the load voltage versus firing angle. Explain and document the result.
2. Single-Phase Full-Wave Rectifiers

Exercise 2.1. Simple M2 rectifier

1. Build a schematic using the function generator, 2 diodes, a resistor, and the ground:
   - connect the positive and negative terminals of the function generator to the diodes’ anodes,
   - join the cathodes and the load input together,
   - ground the load output and the common terminal of the function generator.

2. Add an oscilloscope and connect it for viewing the load voltage $U_d$. To view the load current, add the current-controlled voltage source in series with the load resistor and connect it to the oscilloscope. To measure the average voltage $U_d$ and current $I_d$, add a dc voltmeter across the load and a dc ammeter in series with the load.

3. Calculate the required average load voltage $U_d$ and load current $I_d$ using the Ohm’s low.

4. Calculate the rms supply voltage of each half-winding as follows:
   $$U_s = \pi U_d / (2\sqrt{2}).$$

5. Assign the reference values: $U_s$, $f$, $R_d$.

6. Activate the circuit simulation, measure the load voltage and current, and view both signals: voltage and current. Tune the oscilloscope settings either before or during simulation.

Exercise 2.2. M2 rectifier with LC filter

1. Calculate the peak inverse voltage of the diode as follows:
   $$PIV = \pi U_d.$$  
   In practice, this value will be some lower due to the diode direct voltage drop $U_A$.

2. Measure the peak-to-peak ripple voltage $U_r$ and calculate the ripple factor of the output waveform as follows:
   $$r = U_r / (2U_d).$$

3. For tenfold lowering of the ripple factor ($r_C = r / 10$), add an LC filter built on a capacitor across the load resistor and a reactor in series with the diode and calculate filter parameters (H·µF) as follows:
   $$LC > 2.5 \cdot (r / r_C + 1)$$

4. After activating the circuit, measure the maximum $U_{d_{\text{max}}}$ and minimum $U_{d_{\text{min}}}$ rectified voltages and its average value $U_d$ and calculate the actual ripple factor as follows:
   $$r_C = (U_{d_{\text{max}}} - U_{d_{\text{min}}}) / (2U_d).$$
Exercise 2.3. M2 thyristor rectifier

1. Build the same schematic as in Exercise 2.1 using thyristors instead of diodes and supply it with higher voltage.

2. Build a simple gate driver using a pulse voltage source. Connect the pulse voltage source between the thyristors’ gates and ground. Set its Period = \(1 / (2f)\) and Pulsed value near 2 V.

3. After activating the circuit, view the signals. Use the pulse voltage source as a firing regulator by changing its Delay time. To reduce the firing angle, step down the delay and raise it to enlarge the angle.

4. After activating the circuit, view, explain, and document the result. Then change the load resistance from 10 to 1000 kΩ and build the load curve that is the diagram of the load voltage versus the load current.

5. Build an inductive load by adding an inductor with \(L = 100\) to 1000 mH in series with the load resistor.

6. After activating the circuit, view, explain, and document the result. Again, change the load resistance and build the new load curve.

Exercise 2.4. Simple B2 bridge rectifier

1. Build a schematic using the ac voltage source, 4 diodes \(D_1, D_2, D_1',\) and \(D_2',\) a resistor, the pulse voltage source, and the ground:
   - connect the positive pin of the voltage source to the \(D_1\) anode and \(D_2'\) cathode,
   - connect the negative pin of the source to the \(D_2\) anode and \(D_1'\) cathode,
   - connect the load resistor between the joint cathodes of \(D_1\) and \(D_2,
   - joint the anodes of \(D_1\) and \(D_2'.\)

2. Calculate the required average load voltage \(U_d\) and load current \(I_d\) using the Ohm’s law.

3. Calculate the required rms supply voltage as follows:
   \[
   U_s = \pi U_d / (2\sqrt{2}).
   \]

4. Assign the reference values: \(U_s, f, R_d.\)

5. Add an oscilloscope and connect it to view the load voltage \(U_d.\) For viewing the load current, add the current-controlled voltage source in series with the load resistor and connect it to the oscilloscope also.

6. To measure the average voltage \(U_d\) and current \(I_d,\) add a dc voltmeter across the load and a dc ammeter in series with the load in the previous circuit.

7. Activate the circuit simulation, tune the oscilloscope, and view the load voltage and the load current.

Exercise 2.5. B2 rectifier with LC filter

1. To measure the rms voltage \(U_s\) and current \(I_s,\) add an ac voltmeter across the voltage source and an ac ammeter in series with the voltage source.
2. Measure the peak-to-peak ripple voltage $U_r$ and calculate the ripple factor of the output waveform as follows:

$$r = U_r / (2U_d)$$

3. Calculate the theoretical power factor of the circuit as follows:

$$\cos \varphi = (2\sqrt{2}) / \pi$$

4. After activating the circuit, measure $U_s$, $I_s$, $U_d$, $I_d$, and calculate the experimental power factor $P_d / S$. Compare the calculated and experimental results.

5. For tenfold lowering the ripple factor ($r_C = r / 10$), add an LC filter built on a capacitor across the load resistor and a reactor in series with the diode and calculate filter parameters ($H \cdot \mu F$) as follows:

$$LC = 2.5 \cdot (r / r_C + 1)$$

6. After activating the circuit, measure $U_s$, $I_s$, $U_d$, $I_d$, and calculate the new power factor:

$$\cos \varphi = U_s I_s / (U_d I_d)$$

7. Measure the maximum $U_{d_{\text{max}}}$ and minimum $U_{d_{\text{min}}}$ rectified voltages and calculate the actual ripple factor as follows:

$$r_C = (U_{d_{\text{max}}} - U_{d_{\text{min}}}) / (2U_d)$$

**Exercise 2.6. B2 rectifier with inductive load**

1. Build the same B2 rectifier circuit as in Exercise 2.5.

2. Build an inductive load by adding a variable inductor $L = 50$ to 500 mH in series with the load resistor.

3. After activating the circuit, view, explain, and document the result. Measure the peak-to-peak ripple voltage $U_r$ and the phase shift between the load voltage and current. Build the diagram of the ripple voltage versus an inductance.

4. To compensate the phase shift, add a capacitor across the inductor and find experimentally the capacitance for tenfold lowering the ripple factor.

**Exercise 2.7. B2 thyristor rectifier**

1. Build a schematic using the ac voltage source of higher voltage, 4 thyristors $D_1$, $D_2$, $D_1'$, and $D_2'$, a resistor, the pulse voltage source, and the ground:
   - connect the positive pin of the voltage source to the $D_1$ anode and $D_2'$ cathode,
   - connect the negative pin of the source to the $D_2$ anode and $D_1'$ cathode,
   - connect the load resistor between the joint cathodes of $D_1$ and $D_2$ and the ground,
   - joint the anodes of $D_1$ and $D_2'$.

2. Add an oscilloscope and connect it to view the load voltage $U_d$. To view the load current, add the current-controlled voltage source in series with the load resistor and connect it to the oscilloscope also.
3. To measure the average voltage $U_d$ and current $I_d$, add a dc voltmeter across the load and a dc ammeter in series with the load.

4. Calculate the required average load voltage $U_d$ and load current $I_d$ using the Ohm’s low. Calculate the required rms supply voltage and assign the reference values: $U_s$, $f$, $R_d$.

5. Build the gate driver using the pulse voltage source, which Period is $1 / (2f)$ and Pulse width 1 to 5 ms. Connect its positive pin to the SCR gates and ground the negative pin.

6. After activating the circuit, view the signals and measure the load voltage and current. Use the pulse voltage sources as firing regulators by changing its Delay time.

3. Three-Phase Rectifiers

Exercise 3.1. Simple M3 rectifier

1. Build a schematic using firstly 3 ac voltage sources $U$, $V$, and $W$, 3 diodes, a resistor, and the ground:
   - ground the negative poles of the sources,
   - connect the load resistor between the joint diodes’ cathodes and the ground.

2. Add an oscilloscope and connect it to view the load voltage $U_d$.

3. To view the load current, add the current-controlled voltage source in series with the load resistor and connect it to the oscilloscope.

4. To measure the average voltage $U_d$ and current $I_d$, add a dc voltmeter across the load and a dc ammeter in series with the load.

5. Calculate the required average load voltage $U_d$ and load current $I_d$ using the Ohm’s low.

6. Calculate the required rms supply voltage as follows:

   $$U_s = \frac{2\pi U_d}{3\sqrt{2}\sqrt{3}}.$$

7. Assign the reference values: $U_s$, $f$, $R_d$. Set the necessary phase shifts of each voltage source: 0 degrees for $U$, 240 degrees for $V$, and 120 degrees for $W$.

8. Activate the circuit simulation, tune the oscilloscope settings, and view result.

Exercise 3.2. M3 thyristor rectifier

1. Build the same circuit as in Exercise 3.1 using 3 thyristors $D_U$, $D_V$, and $D_W$ instead of diodes.

2. Build a gate driver using the pulse voltage source between the thyristors’ gates and the ground. Set the pulse voltage source’s Period $1 / (3f)$ and Pulse width 1 to 3 ms.

3. After activating the circuit, view the signals and measure the load voltage and the current. Use the pulse voltage sources as firing regulators by changing its Delay time.

Exercise 3.3. Simple B6 rectifier

1. Build the schematic firstly using 3 ac voltage sources, 6 diodes, and a resistor. Join the negative poles of the three voltage sources $U$, $V$, and $W$ and connect the positive pin of each source to the corresponding pair of diodes:
• source \( U \) to the \( D_u \) anode and \( D_{u'} \) cathode,
• source \( V \) to the \( D_v \) anode and \( D_{v'} \) cathode,
• source \( W \) to the \( D_w \) anode and \( D_{w'} \) cathode.

Connect the load resistor between the joint cathodes of \( D_u, D_v, \) and \( D_w \) and the ground. Also, ground the joint anodes of \( D_{u'}, D_{v'}, \) and \( D_{w'} \).

2. Add an oscilloscope and connect it to view the load voltage \( U_d \).

3. To view the load current, add the current-controlled voltage source in series with the load resistor and connect it to the oscilloscope.

4. To measure average voltage \( U_d \) and current \( I_d \), add a dc voltmeter across the load and a dc ammeter in series with the load.

5. Calculate the required average load voltage \( U_d \) and load current \( I_d \) using the Ohm’s law.

6. Calculate the required rms supply voltage as follows:

\[
U_s = \pi U_d / (3\sqrt{2/3})
\]

7. Assign the reference values: \( U_s, f, R_d \). Set the necessary phase shifts of each voltage source: 0 degrees for \( U \), 120 degrees for \( V \), and 240 degrees for \( W \).

8. Activate the circuit simulation and view result. Tune the oscilloscope settings either before or during simulation.

**Exercise 3.4. B6 thyristor rectifier**

1. Build the same circuit as in Exercise 3.3 using 6 thyristors instead of diodes.

2. Build a gate driver using the pulse voltage source between the thyristors’ gates and ground. Set the pulse voltage source \( \text{Period} = 1 / (3f) \) and \( \text{Pulse width} = 1 \) to 3 ms

3. After activating the circuit, view the signals and measure the load voltage and current.

**4. AC Converters**

**Exercise 4.1. Single-phase voltage regulators**

1. Build a schematic using the ac voltage source, the voltage-controlled switch, a load resistor, the pulse voltage source, and the ground:

   - connect the positive pin of the voltage source to the voltage-controlled switch and ground its negative pin,
   - then connect the load between the voltage-controlled switch and the ground,
   - finally, insert the pulse voltage source between the positive controlling terminal of the voltage-controlled switch and the ground.

2. Assign the values \( U_s, f, R_d \) in accordance with the reference data. In the pulse voltage source set \( \text{Period} = 1 / (2f) \) and \( \text{Pulse width} < \text{Period} \).

3. Add an oscilloscope and connect it for viewing the load voltage \( U_d \). To view the load current, add the current-controlled voltage source in series with the load resistor and connect it to the oscilloscope. To measure the rms load voltage \( U_d \) and current \( I_d \), add an ac voltmeter across the load and an ac ammeter in series with the load.
4. After activating the circuit, view the signals and measure the load voltage and current. Use the pulse voltage source Delay time and Pulse width options as switching regulation options by simultaneous changing of their values as follows:

\[ \text{Period} = \text{Delay time} + \text{Pulse width}. \]

5. By changing these options, build the diagram of the load rms voltage versus delay.

6. Replace the voltage-controlled switch with a pair of thyristors connected back-to-back. Build the own gate driver for each thyristor, placing pulse voltage sources with \( \text{Period} = 1 / (2f) \) between the gate and the cathode.

7. After activating the circuit, view the signals and measure the load voltage and current. Again, build the diagram of the load voltage versus the firing angle. Then, set the firing angle to 45 degrees, vary the load resistance from 1 \( \Omega \) to 1 k\( \Omega \), and build the load curve (load rms voltage versus current) of the system.

Exercise 4.2. Single-Phase Bridge Inverters

1. Build the schematic using the dc voltage source, 4 voltage-controlled switches \( S_1, S_2, S_1', \) and \( S_2' \), the pulse voltage source, a resistor, and the ground:
   - connect the positive pin of the dc voltage source to \( S_1 \) and \( S_2' \) upper terminals,
   - connect the negative pin of the dc voltage source to the \( S_2 \) and \( S_1' \) lower terminals,
   - connect the load resistor between the joint \( S_1 \) and \( S_2 \) terminals and the joint \( S_1' \) and \( S_2' \) terminals, and ground them.

2. Add an oscilloscope and connect it to view the load voltage \( U_d \). To view the load current, add the current-controlled voltage source in series with the load resistor and connect it to the oscilloscope also. To measure the rms voltage \( U_d \) and current \( I_d \), add an ac voltmeter across the load and an ac ammeter in series with the load. Assign the reference values: \( U_s, f, R_d \). Set the on-state resistance of the switch to the minimum allowable value.

3. Build a gate driver using 2 pulse voltage sources:
   - connect the positive terminal of the first pulse voltage source to the positive controlling terminals of the voltage-controlled switches \( S_1, S_1' \),
   - connect the positive terminal of the second voltage source to the positive controlling terminals of the voltage-controlled switches \( S_2, S_2' \).

4. In both pulse voltage sources, set \( \text{Period} = 1 / f \) and \( \text{Pulse width} < \text{Period} / 2 \). In the second pulse voltage source, set \( \text{Delay time} = \text{Period} / 2 \).

5. After activating the circuit, view the ac signals and measure the ac load voltage and current. Change the load frequency by simultaneously varying \( \text{Period} \) option of both pulse voltage sources and \( \text{Delay time} \) of the second pulse voltage source. Change the load voltage by simultaneous varying the \( \text{Pulse width} \) option of both pulse voltage sources. Build the diagram of the load rms voltage versus the duty cycle:

\[ \text{Duty cycle} = 2 \text{Pulse width} / \text{Period}. \]

6. Replace the voltage-controlled switches with 3-terminal enhancement n-MOSFETs. After activating the circuit, view the ac signals and measure the ac load voltage and current.
Build a diagram of the load voltage versus the duty cycle. Then, set the duty cycle to 50%, vary the load resistance from 10 $\Omega$ to 10 k$\Omega$, and build the load curve of the MOSFET system.

**Exercise 4.3. Voltage source and current source inverters**

1. To build a voltage source inverter with ideal switches, use the same schematic as in Exercise 4.2 without the gate driver. Connect an oscilloscope, an ac voltmeter, and an ammeter.

2. Build a new gate driver using the function generator, a comparator, and the ground:
   - set the function generator options as follows: square Waveform, Frequency 50 Hz, Duty Cycle 50%, Amplitude 1 to 10 V, Offset 0,
   - connect the function generator positive terminal to the positive controlling terminals of the voltage-controlled switches $S_1, S_1'$ and the comparator’s negative input,
   - ground the function generator common terminal, negative controlling terminals of each switch, and the comparator’s positive input,
   - connect the opamp output to the positive controlling terminals of the voltage-controlled switches $S_2, S_2'$,

3. After activating the circuit, view the signals and measure the load voltage and current. Change the load frequency by varying the function generator Frequency. Change the load voltage by varying the function generator Duty Cycle option. Build the diagram of the load voltage versus the duty cycle.

4. Replace the voltage-controlled switches with 3-terminal enhancement n-MOSFETs. After activating the circuit, view the signals and measure the load voltage and the current. Build the diagram of the load voltage versus the duty cycle. Then, set the duty cycle to 50%, vary the load resistance from 10 $\Omega$ to 10 k$\Omega$, and build the load curve of the MOSFET system.

5. To build a current source inverter, replace the dc voltage source with a dc current source and repeat the experiment. Change the load current by varying the function generator Duty Cycle option. Build the diagram of the load current versus the duty cycle.

**Exercise 4.4. Frequency converters**

1. Build the same voltage source inverter with ideal switches as in Exercise 4.3.

2. Replace the dc voltage source with the simple bridge rectifier of Exercise 2.4:
   - connect the full-wave bridge rectifier inputs to the ac voltage source,
   - connect the rectifier outputs to $S_1$ and $S_1'$ upper terminals and $S_2$ and $S_2'$ lower terminals,
   - ground the negative terminal of the voltage source.

3. Assign the reference values: $U_s, f, R_d$. Set the function generator options as follows: rectangle Waveform, Frequency <50 Hz, Duty Cycle 50%, Amplitude 1 to 10 V, Offset 0.
4. After activating the circuit, view the signals and measure the load voltage and the current. Change the load frequency by varying the function generator Frequency. Change the load voltage by varying the voltage source Voltage.

5. Replace the voltage-controlled switches with 3-terminal enhancement n-MOSFETs. After activating the circuit, view the signals and measure the load voltage and current. Set Duty Cycle to 50%, vary the load resistance from 10 Ω to 10 kΩ, and build the load curve of the MOSFET system.

6. Insert a little inductive filter in series with the load. Tune the circuit, view the signals, and measure the load voltage and current.

5. Choppers

Exercise 5.1. Step-down choppers

1. Build the schematic using the dc voltage source, the voltage-controlled switch, a load resistor, a capacitor, an inductor, a diode, and the ground:
   - connect the positive pin of the dc voltage source to the voltage-controlled switch and ground its negative pin,
   - connect the inductor and cathode of the flywheel diode to other terminal of the switch and ground the diode anode,
   - connect the capacitor and the load to other terminal of the inductor and ground them also.

2. Calculate the required load voltage $U_d$ and load current $I_d$ using the Ohm’s law. Assign the referenced value of $R_d$ and $U_s = 2U_d$.

3. Add an oscilloscope and connect it to view the load voltage $U_d$. To view the load current, add the current-controlled voltage source in series with the load resistor and connect it to the oscilloscope. To measure the load voltage $U_d$ and current $I_d$, add a dc voltmeter across the load and the dc ammeter in series with the load.

4. Build a gate driver, the Frequency value of which is near 5 kHz.

5. After activating the circuit, view the signals and measure the load voltage and the current. Find the filter properties for tenfold lowering the rms current and voltage. Use the gate driver duty cycle as a switching regulator by changing its value from 0 to 100%. To reduce the load voltage, set the minimum value; to step up the voltage, raise the value. Build the diagram of the load voltage versus the duty cycle.

6. Replace the voltage-controlled switch with the 3-terminal enhancement n-MOSFET. After activating the circuit, view the signals and measure the load voltage and the current. Build the diagram of the load voltage versus the duty cycle. Then, set duty cycle to 50%, vary the load resistance from 10 Ω to 10 kΩ, and build the load curve of the MOSFET system.
**Exercise 5.2. Closed-loop buck chopper**

1. Build the schematic using the dc voltage source $S_1$, the buck converter, a load resistor, and the ground:
   - connect the buck converter between the positive pin of the dc voltage source and the load resistor,
   - ground the negative pin of the dc voltage source and the load.

2. Calculate the required load voltage $U_{d}$ and the load current $I_{d}$ using the Ohm’s law. Assign the referenced value of $R_d$ and $U_s = 2U_d$.

3. Add an oscilloscope and connect it to view the load voltage $U_{d}$. To view the load current, add the current-controlled voltage source in series with the load resistor and connect it to the oscilloscope. To measure the load voltage $U_{d}$ and current $I_{d}$, add a dc voltmeter across the load and a dc ammeter in series with the load.

4. Build a gate driver using the dc voltage source $S_2$, which Voltage value is near 0.5 V. Connect its positive pin to the control terminal of the buck converter and ground the negative pin.

5. After activating the circuit, view the signals and measure the load voltage and the current. Then, vary the load resistance from 10 $\Omega$ to 10 M$\Omega$ and build the load curve that is the diagram of the load voltage versus load current.

6. To stabilize the load voltage, rebuild the gate driver and arrange the negative close loop:
   - set the dc voltage source $S_2$ Voltage value to $U_d$,
   - connect the positive pin of the dc voltage source $S_2$ to the control terminal of the buck converter and the negative pin to the load.

7. After activating the circuit, measure the load voltage and the current. Again, vary the load resistance from 10 $\Omega$ to 10 k$\Omega$ and build the load curve of the closed loop system.

**Exercise 5.3. Step-up choppers**

1. Build the schematic using the dc voltage source, the voltage-controlled switch, a load resistor, a diode, a capacitor, an inductor, and the ground:
   - connect the positive pin of the dc voltage source to the inductor and ground its negative pin,
   - connect the voltage-controlled switch and the diode anode to other terminal of the inductor and ground the switch,
   - then connect the capacitor and the load to the diode cathode and ground them also.

2. Assign the values $U_s$ and $R_d$ in accordance with the reference data. Set the on-state resistance of the switch to minimum allowable value.

3. Add the oscilloscope, the current-controlled voltage source, an ac voltmeter, and an ammeter as in Exercise 5.1.

4. Build the same gate driver as in Exercise 5.1.
5. After activating the circuit, view the signals and measure the load voltage and current. Find the filter properties for tenfold lowering of the rms current and voltage. Use the gate driver’s duty cycle for changing the load voltage. Build the diagram of the load voltage versus the duty cycle.

6. Replace the voltage-controlled switch with the 3-terminal enhancement n-MOSFET. Set the clock \( V_{\text{oltage}} \) value significantly more than \( U_s \). After activating the circuit, view the signals and measure the load voltage and current. Build the diagram of the load voltage versus the duty cycle. Then, set the duty cycle to 50%, vary the load resistance from 10 \( \Omega \) to 10 k\( \Omega \), and build the load curve of the MOSFET system.

**Exercise 5.4. Closed-Loop Boost Chopper**

1. Build a schematic using the dc voltage source \( S_1 \), the boost converter, a load resistor, and the ground:
   - connect the boost converter between the positive pin of the dc voltage source and the load resistor,
   - ground the negative pin of the dc voltage source and the load.

2. Calculate the required load voltage \( U_d \) and the load current \( I_d \) using the Ohm’s law. Assign the referenced value of \( R_d \) and \( U_s = U_d / 2 \).

3. Add an oscilloscope and connect it to view the load voltage \( U_d \). To viewing the load current, add the current-controlled voltage source in series with the load resistor and connect it to the oscilloscope. To measure the load voltage \( U_d \) and current \( I_d \), add a dc voltmeter across the load and a dc ammeter in series with the load.

4. Build a gate driver using the dc voltage source \( S_2 \), the \( V_{\text{oltage}} \) value of which is near 0.5 V. Connect its positive pin to the control terminal of the boost converter and ground the negative pin.

5. After activating the circuit, view the signals and measure the load voltage and current. Then, change the load resistance from 10 \( \Omega \) to 10 M\( \Omega \) and build the load curve that is the diagram of the load voltage versus the load current.

6. To stabilize the load voltage, rebuild the gate driver and arrange the negative feedback:
   - set the \( V_{\text{oltage}} \) value of the dc voltage source \( S_2 \) to \( U_d \),
   - connect the positive pin of the dc voltage source \( S_2 \) to the control terminal of the boost converter and the negative pin to the load.

7. After activating the circuit, measure the load voltage and current. Again, change the load resistance from 10 \( \Omega \) to 10 k\( \Omega \) and build the load curve of the closed loop system.

**Exercise 5.5. Step-down and step-up choppers**

1. Build the schematic using the dc voltage source, the voltage-controlled switch, a load resistor, a diode, a capacitor, an inductor, and the ground:
   - connect the positive pin of the dc voltage source to the voltage-controlled switch and ground its negative pin,
• connect the inductor and the diode cathode to other terminal of the voltage-controlled switch and ground the inductor,
• then connect the capacitor and the load to the diode anode and ground them also.

2. Assign the values $U_s$ and $R_d$ in accordance with the reference data. Set the on-state resistance of the switch to the minimum allowable value.

3. Add an oscilloscope, the current-controlled voltage source, an ac voltmeter, and an ammeter as in Exercise 5.1.

4. Build the same gate driver as in Exercise 5.1.

5. After activating the circuit, view the signals and measure the load voltage and the current. Find the filter properties for tenfold lowering the rms current and voltage. Use the gate driver’s duty cycle for changing the load voltage. Build the diagram of the load voltage versus the duty cycle.

6. Replace the voltage-controlled switch with the 3-terminal enhancement n-MOSFET. Set the clock Voltage value significantly higher than $U_s$. After activating the circuit, view the signals and measure the load voltage and the current. Build the diagram of the load voltage versus the duty cycle. Then, set the duty cycle to 50%, vary the load resistance from 10 $\Omega$ to 10 k$\Omega$, and build the load curve of the MOSFET system.

Exercise 5.6. Closed-loop buck-boost chopper

1. Build the schematic using the dc voltage source $S_1$, the buck-boost converter, a load resistor, and the ground:
   • connect the buck-boost converter between the positive pin of the dc voltage source and the load resistor,
   • ground the negative pin of the dc voltage source and the load.

2. Calculate the required load voltage $U_d$ and load current $I_d$ using the Ohm’s law. Assign the referenced value of $R_d$ and $U_s = U_d$.

3. Add an oscilloscope and connect it to view the load voltage $U_d$. To view the load current, add the current-controlled voltage source in series with the load resistor and connect it to the oscilloscope. To measure the load voltage $U_d$ and current $I_d$, add a dc voltmeter across the load and a dc ammeter in series with the load.

4. Build a gate driver using the dc voltage source $S_2$, the Voltage value of which is near 0.5 V. Connect its negative pin to the control terminal of the boost converter and ground the positive pin.

5. After activating the circuit, view the signals and measure the load voltage and current. Then, change the load resistance from 50 $\Omega$ to 50 k$\Omega$ and build the load curve that is the diagram of the load voltage versus the load current.

6. To stabilize the load voltage, rebuild the gate driver and arrange the negative feedback:
   • set the Voltage value of the dc voltage source $S_2$ to $U_d$,
   • connect the positive pin of the dc voltage source $S_2$ to the control terminal of the boost converter and the negative pin to the load.
7. After activating the circuit, measure the load voltage and the current. Again, change the load resistance from 10 Ω to 10 kΩ and build the load curve of the closed loop system.

Exercise 5.7. Cuk choppers

1. Build the schematic using the dc voltage source, the voltage-controlled switch, a load resistor, a diode, a capacitor, 2 inductors, and the ground:
   - connect the positive pin of the dc voltage source to the first inductor and ground its negative pin,
   - connect the voltage-controlled switch and the capacitor to the other terminal of the inductor and ground the switch,
   - then connect the diode anode and the second inductor to other terminal of the capacitor and ground the diode cathode,
   - finally, connect the load to the other terminal of the second inductor and ground it also.

2. Assign the values $U_s$ and $R_d$ in accordance with the reference data. Set the on-state resistance of the switch to the minimum allowable value.

3. Add an oscilloscope, the current-controlled voltage source, an ac voltmeter, and an ammeter as in Exercise 5.1.

4. Build the same gate driver as in Exercise 5.1.

5. After activating the circuit, view the signals and measure the load voltage and the current. Find the filter properties for tenfold lowering the rms current and the voltage. Use the gate driver’s duty cycle for changing the load voltage. Build the diagram of the load voltage versus the duty cycle.

6. Replace the voltage-controlled switch with the 3-terminal enhancement n-MOSFET. Set the clock Voltage value significantly higher than $U_s$. After activating the circuit, view the signals and measure the load voltage and the current. Build the diagram of the load voltage versus the duty cycle. Then, set the duty cycle to 50%, vary the load resistance from 10 Ω to 10 kΩ, and build the load curve of the MOSFET system.