



POWER DEVICES AND SYSTEMS LABORATORY

Exercise 3U

Buck DC converter

Exercise and manual elaborated by
Łukasz Starzak

Łódź 2020

Contents

B Exercise Introduction	5
1. Exercise Aim and Plan.....	5
C Experiment.....	7
2. Measurements	7
2.1. Measurement set-up	7
2.2. Preparation for measurements.....	9
Configuring the measurement set-up	9
Supplying the unloaded circuit	9
Configuring the oscilloscope and generator	11
Supplying the loaded circuit	11
2.3. Converter component roles	13
Output voltage measurement without inductor and capacitor	13
Current measurement without inductor and capacitor.....	13
Effect of passive components on circuit operation.....	14
Single-pole double-throw semiconductor switch	15
2.4. Buck circuit as a converter of electrical energy.....	16
Waveforms under nominal conditions	16
Reconfiguring the measurement set-up.....	16
Measuring static characteristics.....	18
2.5. Terminating measurements.....	19
D Results	21
3. Processing and Analysing Results.....	21
3.1. Buck converter topology	21
Semiconductor switch	21
Circuit component roles	21
Operating parameters under nominal conditions.....	21
3.2. Circuit characteristics and effect of transistor	22
Efficiency	22
Voltage conversion ratio.....	22
Input current.....	22
Transistor power loss minimisation	22
E Information	23
4. Required Knowledge.....	23
4.1. Prerequisites	23
4.2. Test scope.....	23
5. References	23

Exercise Introduction

1. Exercise Aim and Plan

The aim of this exercise is to get acquainted with the operation of one of the most common power electronic converters: the DC converter, which at the same time is a typical application of the power MOSFET. In this specific case, the non-isolated (transformerless) step-down (buck) circuit will be investigated, which has the simplest topology and operating principle among DC converters. As in any DC converter, the transistor is there a component of a single-pole double-throw (SPDT) semiconductor switch whose role is to switch over a current from one branch to another one. Based on this example, the pulse width modulation (PWM) method of controlling power semiconductor devices will be illustrated.

This exercise demonstrates that the switched-mode technique using power transistors enables to accomplish useful functions in DC circuits while achieving high energy conversion efficiency. However, obtaining a functional circuit is impossible without using passive power components, whose role will also be experimentally investigated.

The DC converter designed and assembled in the frame of Exercise 7K will be the specific object of investigation. It is also in the manual for Exercise 7K that theoretical material necessary for carrying out this exercise has been provided or referenced.

2. Measurements

2.1. Measurement set-up

The schematic diagram of the non-isolated buck (step-down) converter has been presented in Fig. 1. Screw terminal blocks enable the connection of a **power supply** (terminal block J₁, input voltage U_i) and of a **load** R_L (terminal block J₂, output voltage u_o). It should be noted that the voltages U_i and u_o also appear across the capacitors C₁ and C₅, respectively, that are polar components, which requires the correct polarity of the input voltage to be assured. To supply the circuit, any power supply with a current capability of at least 3 A, smoothly adjustable voltage and adjustable current limit can be used.

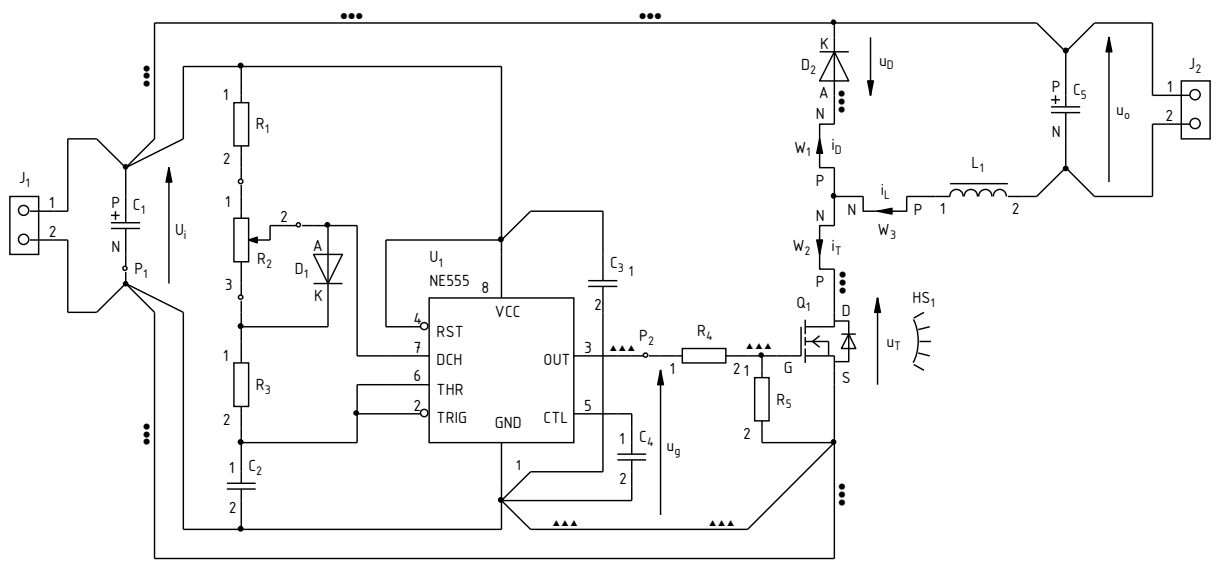


Fig. 1. Schematic diagram of the buck converter circuit under investigation

From among the **components of the power loop**, it will be the semiconductor switch, i.e. the transistor T and the diode D, as well as the output capacitor C_1 that will operate constantly. The inductor L_1 will initially be shorted whereas the output capacitor C_5 will be disconnected from the circuit (unmounted component or one terminal desoldered). These components will be restored to the circuit over the course of the exercise.

The **pulse wave** controlling the transistor u_g comes from an embedded generator. The potentiometer R_2 enables the duty cycle of this waveform to be set.

The measurement point P_1 , connected to the circuit's **ground**, will be used to attach voltage probe grounds. The measurement point P_2 enables the generator **voltage** to be measured. Other voltages will be measured at the J_1 and J_2 terminal blocks.

Observing **current** waveforms is possible by clamping a current probe around one of the wires led out of the board: W_1 for the diode current i_D , W_2 for the transistor current i_T or W_3 for the inductor current i_L .

Depending on the stand, a four-channel or a two-channel **oscilloscope** may be used. In the latter case, due to the limited number of channels, it will be necessary to switch over voltage and current probes, additionally using the external trigger input. Measurement procedures are described further in this manual, along with oscilloscope model designations when procedures differ.

2.2. Preparation for measurements

Configuring the measurement set-up

A simplified block diagram of the measurement set-up, including the two possible oscilloscope models is presented in Fig. 2. It should be assembled and configured in the way described below and in the specified sequence. If an oscilloscope model designation is given in a given step, then this step concerns this specific model, while it should not be carried out in case another model is used.

In order not to waste time, you should continue with following steps in parallel with step 1.

1. Switch the computer on. After logon completes, switch the oscilloscope on and, if necessary, set up its connection to the computer following a manual available at the laboratory stand.
2. In the converter board, keep the output capacitor C_5 disconnected and the inductor L_1 shorted. Keep the terminals of the block J_2 unoccupied.
3. Switch the power supply on without activating its output.
4. Connect the power supply's output with the converter's input (U_i voltage), i.e. with the terminal block J_1 , minding the polarity of the capacitor C_1 .
5. Using a multimeter set to its circuit continuity test mode, verify that the „+” terminal of the power supply is connected to the VCC pin (pin 8) of the integrated circuit U_1 and that its „-” terminal is connected to the GND pin (pin 1).
6. Attach the voltage probe or probes with a 1:10 attenuation, connected to the input or inputs of the oscilloscope, so as to measure the generator's output voltage u_g (measurement points P_1 and P_2), considering its direction according to Fig. 1:
 - [TBS2104] in channel 3;
 - [TBS1052B, TBS1072B] in the external trigger channel (*Ext Trig*) and in channel 1.

Voltage probe grounds (alligator clip connectors) are shorted together inside the oscilloscope and connected to the supply network protective earth. They must be therefore always connected to the same electric potential. Any other connection might result in current flowing through the oscilloscope, which would damage its input circuitry!

Supplying the unloaded circuit

7. Within your results of Exercise 7K (Task 7), check out the expected input current of an unloaded converter (or calculate it again as the sum of the maximum supply current of the integrated circuit U_1 according to its documentation and the maximum current of the generator's RC network as assumed in design.

While executing the following step, pay attention not to exceed the value of 18 V at any moment, as this might damage the integrated circuit U_1 .

8. Supply the unloaded converter:
 - (a) if a multi-channel power supply is used, select the channel used with the *Local/CH* button;
 - (b) push *I-Set* and set the current limit to 100 mA;
 - (c) push *V-Set* and set the voltage to 0 V;
 - (d) activate the output with the *On/Off* button and display embedded meter indications with the *Meter* button;

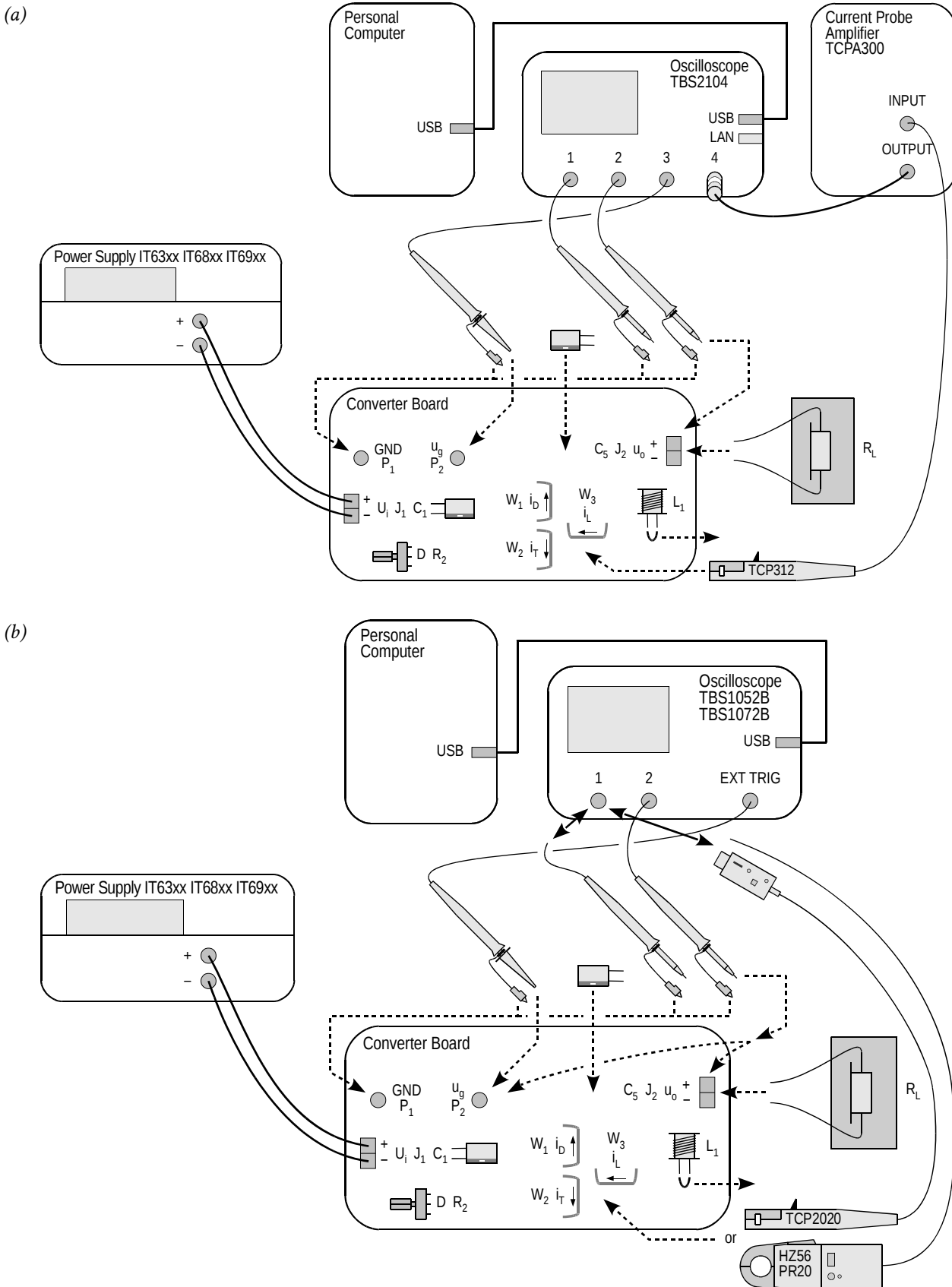


Fig. 2. Block diagram of the measurement set-up for recording time waveforms: (a) with a TBS2104 oscilloscope; (b) with a TBS1052B or TBS1072B oscilloscope

Read the contents of the following step in their entirety first and only then proceed with its execution.

- (e) using the knob, gradually increase the supply voltage to the nominal value of the input voltage U_i , watching that the current indicated by the power supply's ammeter does not significantly (by more than 50%) exceed the expected value as established in step 7; otherwise, deactivate the power supply's output with the *On/Off* button and verify your connections again.

Configuring the oscilloscope and generator

9. Using the oscilloscope communication software, upload initial settings to the oscilloscope:
- go to the *Get & Send Settings* tab;
 - click *Open* and read the file *ustawienia_3u_tbs2104 Ug_uo_il.set* or *ustawienia_3u_TBS1052B_Ug_uo.set*, as appropriate;
 - click *Send Settings*.

In the oscilloscope's screen, a stable, continuously refreshed pulse wave should be displayed, as attested, among others, by the message "Trig'd" (*Triggered*) appearing above the graticule. If this does not happen, ask the teacher to check oscilloscope settings.

10. In case of need, adjust:
- the time base and the trigger event position (*Horizontal Scale* and *Horizontal Position* knobs) so that 3 to 7 periods of the u_g voltage are visible; the trigger instant, indicated by an arrow at the top of the graticule, must appear within the screen, i.e. it cannot be located at either end of the graticule;
 - gain and zero level position (*Vertical Scale* and *Position* knobs) of the channel where the generator voltage is measured so that its waveform is easily observed, is located at the very bottom of the screen and extends vertically over approximately one division.
11. Using the potentiometer R_2 , using the *Pos Duty* or *Pos. Duty Cycle* measurement result displayed on the oscilloscope, coarsely set half of the expected nominal (i.e. one corresponding to the nominal input voltage U_i) duty cycle as calculated in Exercise 7K (Task 4).

Setting a duty cycle higher than the one indicated above at this moment may cause the transistor or the diode to be destroyed as a result of excessive power dissipation in the circuit where output passive components are absent. It will be only possible to increase the duty cycle at a specified moment after passive components are connected.

12. Bring the supply voltage down to zero.

Suppling the loaded circuit

13. To the converter's output (terminal block J_2), attach a load in the form of a resistor, or a set of resistors, having a resistance such that at the nominal output voltage U_o as assumed in design, the assumed nominal output current I_o is obtained, and having a resultant admissible power of at least twice the nominal output power of the converter.
14. Place the load on a heat resistant pad. Ensure that no component or wire touches the load; this equally applies to voltage and current probe cables. Otherwise, wire or termination insulation can melt.

The above conditions must be kept ensured over the entire course of this exercise!

Do not touch the load while realising this exercise, as, depending on operating conditions, its temperature can rise above 100 °C. Risk of burn!

15. Calculate the expected input current of the loaded converter for the duty cycle D set above, the nominal input voltage U_i and the resistance of the load used R_L (see Exercise 7K, Task 8).
16. On the power supply, push *I-Set* and set current limit to 3 A.

17. Push *V-Set* and gradually restore the nominal input voltage U_i , watching that the current does not significantly (by more than 20%) exceed the expected value as established in step 15; otherwise, de-activate the power supply's output with the *On/Off* button and verify the circuit again.

From this moment on, all until the completion of the exercise, under no circumstances should a different time base (*Horizontal Scale* knob) or trigger instant position (*Horizontal Position* knob) be set! This would cause de-synchronisation between consecutive oscilloscope images, thus rendering their analysis impossible at the result processing stage.

From this moment on, the duty cycle of the generator voltage (thus the setting of the potentiometer R_2) should not be changed unless you are explicitly told to! This would cause an inconsistency between consecutive oscilloscope images, thus rendering their analysis impossible at the result processing stage.

2.3. Converter component roles

Output voltage measurement with inductor and output capacitor absent

1. [TBS1052B, TBS1072B] Na oscyloskopie zachowaj obraz napięcia u_g :
 - (a) save the control voltage waveform u_g in the oscilloscope's memory:
 - push *Save Recall*,
 - using the appropriate button beside the screen, set *Action* to *Save Waveform*,
 - select saving to oscilloscope memory, *Save To: Ref*,
 - set *Source* to channel 1 (*CH1*),
 - select destination as Memory A, *To: Ref A*,
 - push *Save*;
 - (b) display the u_g waveform from the Memory A by pushing *R* and then, using an appropriate button beside the screen, set *Ref A* to *On*; as a result, the waveform observed previously should become duplicated in a different colour (this may be verified by slightly moving the waveform of channel 1 with the *Vertical Position* knob).
2. Set up output voltage measurement as the difference of output terminal voltages:
 - (a) [TBS1052B, TBS1072B] with the *Vertical Scale* knob, change the channel 1 gain to 5 V/div, then hide the channel 1 waveform with the *1* button;
 - (b) [TBS2104] with the buttons *1* and *2*, display channel 1 and 2 waveforms;
 - (c) with the *M* button, show the mathematical operation waveform and ensure that settings displayed in the right-hand side of the screen indicate that this waveform corresponds to the difference of channel 1 and 2 waveforms (*Ch1 – Ch2*);
 - (d) if necessary, set the scale of the mathematical operation waveform to 5 V/div by selecting *Vertical Scale* with an appropriate button beside the screen and set the value with the *Multipurpose* knob.
3. Attach the grounds of both voltage probes from channels 1 and 2 to the point P₁ (if this has not been already done). With the needle tips (after caps are taken off) of the channel 1 and 2 voltage probes, touch the terminals 1 and 2, respectively, of the terminal block J₂.
 In the screen, as the mathematical operation waveform M, the waveform of the converter's output voltage u_o should be displayed. Make sure that the sign of this voltage as measured conforms to the operating principle of the circuit under investigation.
4. Without modifying any settings in the circuit or on the oscilloscope, record the oscilloscope image of the waveforms u_g and u_o in a graphical form
 - in the OpenChoice Desktop application, go to the *Screen Capture* tab;
 - download the screen image to the computer by clicking *Get Screen*;
 - save the oscilloscope image in a graphical form by clicking *Save As*.
5. Disconnect channel 1 and 2 probes from the circuit.
6. Save the resulting ultimate oscilloscope settings for voltage measurements, to a file:
 - go to the *Get & Send Settings* tab;
 - click *Get Settings*;
 - click *Save As* and save the file in your team account.

Current measurement with inductor and output capacitor absent

7. [TBS1052B, TBS1072B] Modify the measurement set-up to enable currents to be measured:
 - (a) upload settings appropriate for current measurements to the oscilloscope:
 - click *Open* and read the file *ustawienia_3u_TBS1052B_il.set*,

- click *Send Settings*;
- (b) detach the voltage probe from channel 1 (without disconnecting it from the circuit);
 - (c) attach the current probe to channel 1 and configure this probe according to the instruction manual available at the laboratory stand.
8. [TBS2104] Set up current measurement:
- (a) attach the output of the current probe amplifier to channel 4 of the oscilloscope;
 - (b) switch the current probe amplifier on and set it up according to the instruction manual available at the laboratory stand, selecting a current-to-voltage conversion ratio appropriate for a current value equal to the output current assumed in design;
 - (c) on the oscilloscope, with buttons *1*, *2*, *M* and *4*, hide channel 1 and 2 waveforms as well as the mathematical operation waveform, and show the channel 4 waveform.
9. Clamp the probe on the wire conducting the current of the inductor (presently shorted) i_L (wire W_3) so that the positive current direction as indicated by an arrow on the probe body is in accordance with the arrow in Fig. 1. A waveform of the current i_L should be displayed on the oscilloscope. Make sure that the sign of the current as measured is positive, which indicates that the probe has been oriented correctly.
10. Supposing that the transistor is an ideal switch, estimate its expected on-state current, considering that the inductor L_1 and the capacitor C_5 are absent from the circuit (i.e., shorted or opened, respectively).
- Check whether the value indicated on the oscilloscope, according to the scale of the respective channel, conforms to this expectation. Otherwise, determine and eliminate the source of such a discrepancy (e.g. incorrectly calculated or applied load resistance, incorrect input or output voltage, incorrect current probe or oscilloscope settings).
11. Without modifying any settings in the circuit or on the oscilloscope, record an oscilloscope image of the u_g and i_L waveforms in a graphical form:
- in the OpenChoice Desktop application, go to the *Screen Capture* tab;
 - download the screen image to the computer by clicking *Get Screen*;
 - save the oscilloscope image in a graphical form by clicking *Save As*.
12. Save the resulting ultimate oscilloscope settings for current measurements, to a file:
- go to the *Get & Send Settings* tab;
 - click *Get Settings*;
 - click *Save As* and save the file in your team account.

Effect of passive components on circuit operation

13. Insert the inductor into the converter circuit:
- (a) bring the input voltage down to zero;
 - (b) unclamp the current probe from the wire;
 - (c) eliminate the short between the terminals of the inductor L_1 ;
 - (d) restore the nominal value of the input voltage U_i , watching that the expected input current still is not significantly exceeded;
 - (e) clamp the current probe back so that to measure the current i_L (wire W_3) considering its direction;
 - (f) verify that the direction (sign) of the current is correct as indicated on the oscilloscope.
14. Without modifying any settings in the circuit or on the oscilloscope, record an oscilloscope image of the u_g and i_L waveforms in a graphical form.
15. [TBS1052B, TBS1072B] Detach the current probe from channel 1 of the oscilloscope (without switching this probe off); and in its place, attach the voltage probe back.

16. Measure the output voltage:
 - (a) through the *Get & Send Settings* tab, from the file saved in step 6, read and upload the voltage measurement settings;
 - (b) with needle tips of the channel 1 and 2 voltage probes, touch the terminals 1 and 2, respectively, of the terminal block J₂;
 - (c) through the *Screen Capture* tab, record an oscilloscope image of the u_g and u_o waveforms in a graphical form.
17. Insert the output capacitor into the converter circuit:
 - (a) bring the input voltage down to zero;
 - (b) unclamp the current probe from the wire;
 - (c) at the appropriate location on the board, solder the capacitor C₅ minding its polarity;
 - (d) using a multimeter set to its circuit continuity test mode, make sure that the “+” terminal of the power supply is connected with the positive terminal of the capacitor C₅;
 - (e) restore the nominal value of the input voltage U_i , watching that the expected input current still is not significantly exceeded;
18. Without modifying any settings in the circuit or on the oscilloscope, record a new oscilloscope image of the u_g and u_o waveforms in a graphical form.
19. Put caps back to the tips of the channel 1 and 2 voltage probes.
20. [TBS1052B, TBS1072B] Detach the voltage probe from channel 1 of the oscilloscope; in its place, attach the current probe back.
21. Measure the inductor current:
 - (a) through the *Get & Send Settings* tab, from the file saved in step 12, read and upload the current measurement settings;
 - (b) clamp the current probe back so that to measure the current i_L (wire W₃) considering its direction
 - (c) verify that the direction (sign) of the current is correct as indicated on the oscilloscope;
 - (d) through the *Screen Capture* tab, record an oscilloscope image of the u_g and i_L waveforms in a graphical form.

Single-pole double-throw semiconductor switch

22. Move the current probe to the wire conducting the diode current i_D , minding its direction according to Fig. 1. Verify that the direction indicated on the oscilloscope is correct.
23. Without modifying any settings in the circuit or on the oscilloscope, record a new oscilloscope image of the u_g and i_D waveforms in a graphical form.
24. Move the current probe to the wire conducting the transistor current i_T , minding its direction according to Fig. 1. Verify that the direction indicated on the oscilloscope is correct.
25. Without modifying any settings in the circuit or on the oscilloscope, record a new oscilloscope image of the u_g and i_T waveforms in a graphical form.

2.4. Buck circuit as a converter of electrical energy

Waveforms under nominal conditions

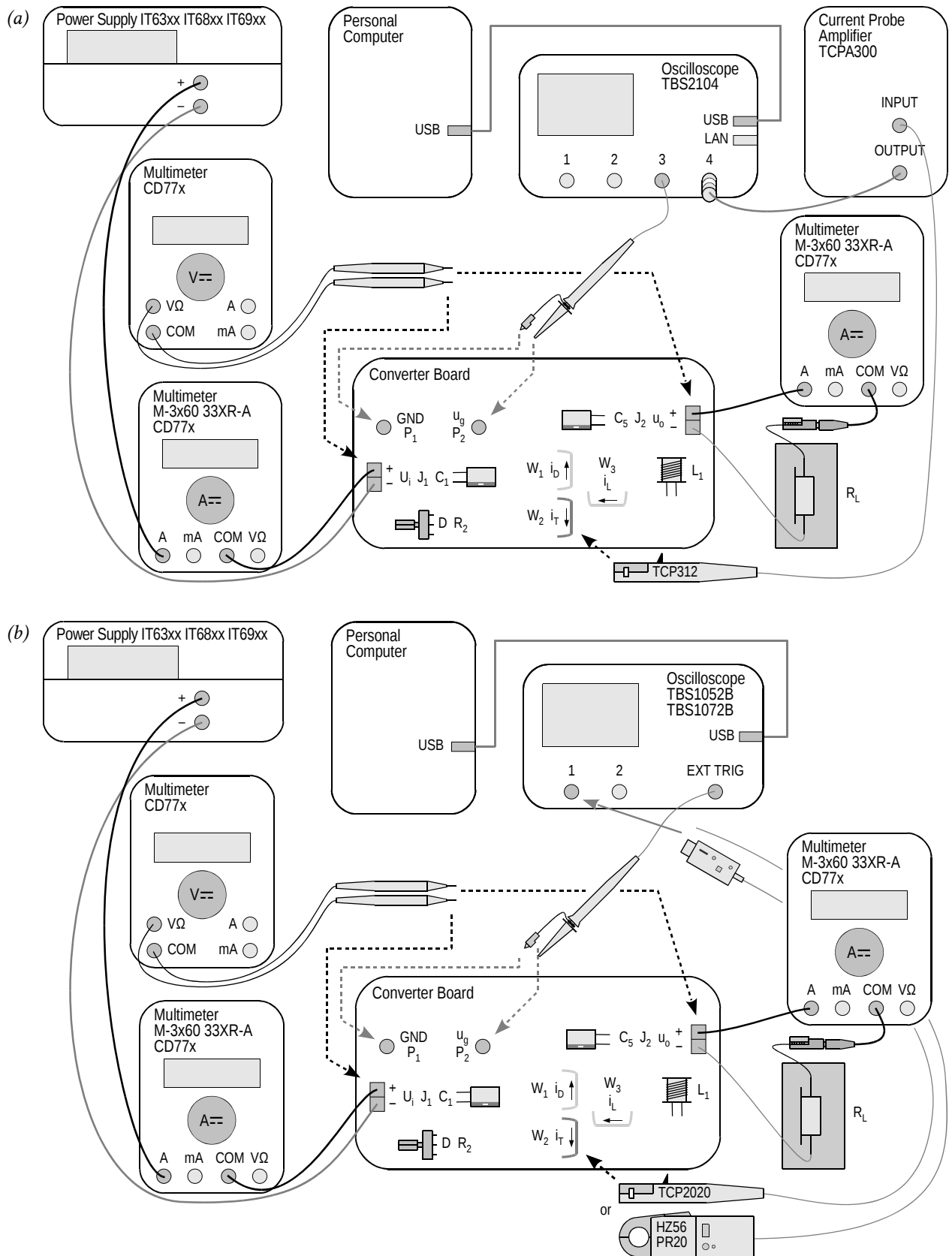
1. By measuring the input voltage U_i with a multimeter in the terminal block J₁, ensure that its value is equal to the nominal one with an accuracy of ± 0.1 V.
2. Using the potentiometer R_2 , modify the duty cycle so that to obtain the nominal value of the output voltage U_o as assumed in design with an accuracy of ± 0.1 V, by measuring this voltage with a multimeter in the terminal block J₂.
3. Move the current probe to the wire conducting the inductor current i_L , minding its direction according to Fig. 1. Verify that the direction indicated on the oscilloscope is correct.
4. Without modifying any settings in the circuit or on the oscilloscope, record a new oscilloscope image of the u_g and i_L waveforms in a graphical form.
5. [TBS1052B, TBS1072B] Detach the current probe from channel 1 of the oscilloscope (without switching this probe off); in its place, attach the voltage probe back.
6. Measure the output voltage:
 - (a) through the *Get & Send Settings* tab, from the file saved in step 6, read and upload the voltage measurement settings;
 - (b) with needle tips of the channel 1 and 2 voltage probes, touch the terminals 1 and 2, respectively, of the terminal block J₂;
 - (c) through the *Screen Capture* tab, record an oscilloscope image of the u_g and u_o waveforms in a graphical form.

Reconfiguring the measurement set-up

A block diagram of the measurement set-up is presented in Fig. 3. Connections to be made or modified, in the way described below, are marked in black, while grey lines show existing connections to be kept unchanged.

7. [TBS1052B, TBS1072B] Detach the voltage probe from channel 1 of the oscilloscope; in its place, attach the current probe back.
8. Set up transistor current measurement:
 - (a) move the current probe to the wire conducting the transistor current i_T , minding its direction according to Fig. 1; verify that the direction indicated on the oscilloscope is correct;
 - (b) through the *Get & Send Settings* tab, from the file saved in step 12, read and upload the current measurement settings;
 - (c) [TBS2104] activate the measurement of the duty cycle of the current:
 - push *Measure*;
 - with an appropriate button beside the screen, select *Ch3*, then with the *Multipurpose* knob, de-select the item *+Duty*;
 - with a button beside the screen, select *Ch4*, then with the *Multipurpose* knob, select the item *+Duty*;
 - close the menu with the *Menu On/Off* button.
9. Bring the input voltage down to zero.
10. Adapt the set-up for measuring the input and output currents:
 - (a) in series with the input, i.e. between the power supply and the terminal block J₁, and in series with the output, i.e. between the terminal block J₂ and the load, insert two multimeters of the same model in a way enabling currents to be measured up to the value expected for the output current, i.e. ensuring that appropriate sockets are used;

- (b) set the multimeters to the DC current measurement mode, considering the expected value as above.



Measuring static characteristics

Before continuing, the wiring of the multimeters must be verified by the teacher.

11. Restore the nominal input voltage.

During the execution of the following step, exceeding the value of 18 V during adjustment, even momentarily, may cause the integrated circuit U_1 to be damaged!

If a discharged battery indicator (battery symbol) shows up on the multimeter's display, do not go on with measurements, but inform the teacher in order to replace the battery. Otherwise multimeter indications may become erroneous.

12. For 5 to 10 measurement points defined by the value of the input voltage varied within the range determined in design, from the maximum towards the minimum (not in the opposite direction), among which values the nominal value assumed in design must appear:

- (a) on the power supply, set the selected input voltage;
- (b) with the potentiometer R_2 , set the duty cycle so that to obtain the nominal value of the output voltage U_o , by measuring the DC value of this voltage in the terminal block J_2 using a third multimeter;
- (c) from the oscilloscope, read out and write down the duty cycle of the transistor current D_{π} (*Pos Duty* or *Pos. Duty Cycle* indication);
- (d) from the multimeters, read out and write down DC values of the input current I_i and of the output current I_o ;
- (e) using the third multimeter, measure and write down the DC value of the input voltage U_i (at the terminal block J_i) and of the output voltage U_o (in the terminal block J_2).

2.5. Terminating measurements

1. Using the potentiometer R_2 , decrease the duty cycle to its minimum.
2. Bring the power supply voltage down to zero and de-activate its output with the *On/Off* button.
3. Switch the power supply off.
4. Detach the current probe from the circuit.
5. Switch the current probe off in a way appropriate for the model used.
6. [TBS2104] Do not disconnect the current probe from its amplifier or the probe amplifier from the oscilloscope.
[TBS1052B, TBS1072B] Disconnect the current probe from the oscilloscope.
7. Disconnect voltage probes from the circuit. Do not disconnect them, however, from the oscilloscope.
8. Disconnect the circuit from the power supply.
9. Disconnect the load from the circuit.

3. Processing and Analysing Results

3.1. Buck converter topology

Semiconductor switch

1. In Part 1 of the report, include oscilloscope images enabling waveforms of component currents and of the control voltage to be compared against each other: $\{u_g, i_L\}$, $\{u_g, i_D\}$ and $\{u_g, i_T\}$ as recorded in steps 2.3/21, 23 and 25, respectively.
2. Complete Part 1 of the report.

Circuit component roles

3. In Part 2 of the report, set together oscilloscope images recorded in Section 2.3: with the output passive components effectively eliminated (steps 4 and 11), after the short between the inductor's terminals was eliminated (steps 14 and 16) and after the output capacitor was soldered in (steps 18 and 21).
4. Fill in Part 2 of the report.

Operating parameters under nominal conditions

5. Fill in Part 3 of the report.

3.2. Circuit characteristics and effect of transistor

Efficiency

1. Based on your results of measurements performed in step 2.4/12, calculate for each measurement point (see Manual 7K, Sub-chapter 5.5):
 - (a) average input power P_i , from appropriate voltage and current measured (assuming that the input voltage is constant in time);
 - (b) average output power P_o , from appropriate voltage and current measured (assuming that the output voltage is constant in time);
 - (c) efficiency η , from its definition;
 - (d) voltage conversion ratio K_U , from its definition;
 - (e) * current conversion ratio K_I , defined as

$$K_I = \frac{I}{I_{g(0)}} \quad (3.1)$$

2. For each value of the duty cycle D_{IT} , calculate:
 - (a) voltage conversion ratio of an ideal (lossless) converter $K_{U(id)}$, from the analytical formula (see Manual 7K, Sub-chapter 5.2);
 - (b) the ratio of $K_U / K_{U(id)}$, based on your results from sub-steps (a) and 1(d).
3. Collect measurement and calculation results in appropriate tables in Part 4 of the report.
4. Complete Part 4 of the report.

Voltage conversion ratio

5. For a dense set of values of the duty cycle D_{IT} covering their entire possible range, i.e. [0; 1], so that it is later possible to plot a characteristic in the entire range of 0 to 1, making the impression of a smooth line, calculate again the voltage conversion ratio of an ideal converter $K_{U(id)}$ [see step 2(a)]. Put the values obtained in the appropriate table in Part 5 of the report.
6. Complete Part 5 of the report.

Input current

7. * For a dense set of values of the duty cycle D_{IT} covering their entire possible range, i.e. [0; 1], so that it is later possible to plot a characteristic in the entire range of 0 to 1, making the impression of a smooth line, calculate theoretical values of the current conversion ratio K_I by expressing the direct component of the input current $I_{g(0)}$ in the definition (3.1) as a function of the output current using the analytical formula (see 7K, Sub-chapter 5.5). Put the values obtained in the appropriate table in Part 6 of the report.
8. Fill in Part 6 of the report.

Transistor power loss minimisation

9. Fill in Part 7 of the report.

4. Required Knowledge

4.1. Prerequisites

- Buck converter operation (circuit without passive component, with the inductor, and with the output capacitor): electrical schematic, voltage and current waveforms and values with special emphasis on output voltage and input current (Manual 7K, Refs. B and C, Sections 5.2, 5.4 and 5.5)

4.2. Test scope

The problem scope related to this exercise is common with Exercise 7K; it has been given in Manual 7K.

5. References

- [1] Benda V., Gowar J., Grant D. A.: *Power Semiconductor Devices: Theory and Applications*. Wiley, 1999. ISBN 0-471-97644-X.
- [3] Erickson R. W., Maksimović D.: *Fundamentals of Power Electronics. Second Edition*. Springer, 2001. ISBN 0-792-37270-0.



POWER DEVICES AND SYSTEMS LABORATORY

Exercise 3U

Buck DC converter

Exercise and manual elaborated by
Łukasz Starzak

Łódź 2020

Contents

B Exercise Introduction	5
1. Exercise Aim and Plan.....	5
C Experiment.....	7
2. Measurements	7
2.1. Measurement set-up	7
2.2. Preparation for measurements.....	9
Configuring the measurement set-up	9
Supplying the unloaded circuit	9
Configuring the oscilloscope and generator	11
Supplying the loaded circuit	11
2.3. Converter component roles	13
Output voltage measurement without inductor and capacitor	13
Current measurement without inductor and capacitor.....	13
Effect of passive components on circuit operation.....	14
Single-pole double-throw semiconductor switch	15
2.4. Buck circuit as a converter of electrical energy.....	16
Waveforms under nominal conditions	16
Reconfiguring the measurement set-up.....	16
Measuring static characteristics.....	18
2.5. Terminating measurements.....	19
D Results	21
3. Processing and Analysing Results.....	21
3.1. Buck converter topology	21
Semiconductor switch	21
Circuit component roles	21
Operating parameters under nominal conditions.....	21
3.2. Circuit characteristics and effect of transistor	22
Efficiency	22
Voltage conversion ratio.....	22
Input current.....	22
Transistor power loss minimisation	22
E Information	23
4. Required Knowledge.....	23
4.1. Prerequisites	23
4.2. Test scope.....	23
5. References	23

Exercise Introduction

1. Exercise Aim and Plan

The aim of this exercise is to get acquainted with the operation of one of the most common power electronic converters: the DC converter, which at the same time is a typical application of the power MOSFET. In this specific case, the non-isolated (transformerless) step-down (buck) circuit will be investigated, which has the simplest topology and operating principle among DC converters. As in any DC converter, the transistor is there a component of a single-pole double-throw (SPDT) semiconductor switch whose role is to switch over a current from one branch to another one. Based on this example, the pulse width modulation (PWM) method of controlling power semiconductor devices will be illustrated.

This exercise demonstrates that the switched-mode technique using power transistors enables to accomplish useful functions in DC circuits while achieving high energy conversion efficiency. However, obtaining a functional circuit is impossible without using passive power components, whose role will also be experimentally investigated.

The DC converter designed and assembled in the frame of Exercise 7K will be the specific object of investigation. It is also in the manual for Exercise 7K that theoretical material necessary for carrying out this exercise has been provided or referenced.

From among the **components of the power loop**, it will be the semiconductor switch, i.e. the transistor T and the diode D, as well as the output capacitor C_1 that will operate constantly. The inductor L_1 will initially be shorted whereas the output capacitor C_5 will be disconnected from the circuit (unmounted component or one terminal desoldered). These components will be restored to the circuit over the course of the exercise.

The **pulse wave** controlling the transistor u_g comes from an embedded generator. The potentiometer R_2 enables the duty cycle of this waveform to be set.

The measurement point P_1 , connected to the circuit's **ground**, will be used to attach voltage probe grounds. The measurement point P_2 enables the generator **voltage** to be measured. Other voltages will be measured at the J_1 and J_2 terminal blocks.

Observing **current** waveforms is possible by clamping a current probe around one of the wires led out of the board: W_1 for the diode current i_D , W_2 for the transistor current i_T or W_3 for the inductor current i_L .

Depending on the stand, a four-channel or a two-channel **oscilloscope** may be used. In the latter case, due to the limited number of channels, it will be necessary to switch over voltage and current probes, additionally using the external trigger input. Measurement procedures are described further in this manual, along with oscilloscope model designations when procedures differ.

2.2. Preparation for measurements

Configuring the measurement set-up

A simplified block diagram of the measurement set-up, including the two possible oscilloscope models is presented in Fig. 2. It should be assembled and configured in the way described below and in the specified sequence. If an oscilloscope model designation is given in a given step, then this step concerns this specific model, while it should not be carried out in case another model is used.

In order not to waste time, you should continue with following steps in parallel with step 1.

1. Switch the computer on. After logon completes, switch the oscilloscope on and, if necessary, set up its connection to the computer following a manual available at the laboratory stand.
2. In the converter board, keep the output capacitor C_5 disconnected and the inductor L_1 shorted. Keep the terminals of the block J_2 unoccupied.
3. Switch the power supply on without activating its output.
4. Connect the power supply's output with the converter's input (U_i voltage), i.e. with the terminal block J_1 , minding the polarity of the capacitor C_1 .
5. Using a multimeter set to its circuit continuity test mode, verify that the „+” terminal of the power supply is connected to the VCC pin (pin 8) of the integrated circuit U_1 and that its „-” terminal is connected to the GND pin (pin 1).
6. Attach the voltage probe or probes with a 1:10 attenuation, connected to the input or inputs of the oscilloscope, so as to measure the generator's output voltage u_g (measurement points P_1 and P_2), considering its direction according to Fig. 1:
 - [TBS2104] in channel 3;
 - [TBS1052B, TBS1072B] in the external trigger channel (*Ext Trig*) and in channel 1.

Voltage probe grounds (alligator clip connectors) are shorted together inside the oscilloscope and connected to the supply network protective earth. They must be therefore always connected to the same electric potential. Any other connection might result in current flowing through the oscilloscope, which would damage its input circuitry!

Supplying the unloaded circuit

7. Within your results of Exercise 7K (Task 7), check out the expected input current of an unloaded converter (or calculate it again as the sum of the maximum supply current of the integrated circuit U_1 according to its documentation and the maximum current of the generator's RC network as assumed in design.

While executing the following step, pay attention not to exceed the value of 18 V at any moment, as this might damage the integrated circuit U_1 .

8. Supply the unloaded converter:
 - (a) if a multi-channel power supply is used, select the channel used with the *Local/CH* button;
 - (b) push *I-Set* and set the current limit to 100 mA;
 - (c) push *V-Set* and set the voltage to 0 V;
 - (d) activate the output with the *On/Off* button and display embedded meter indications with the *Meter* button;

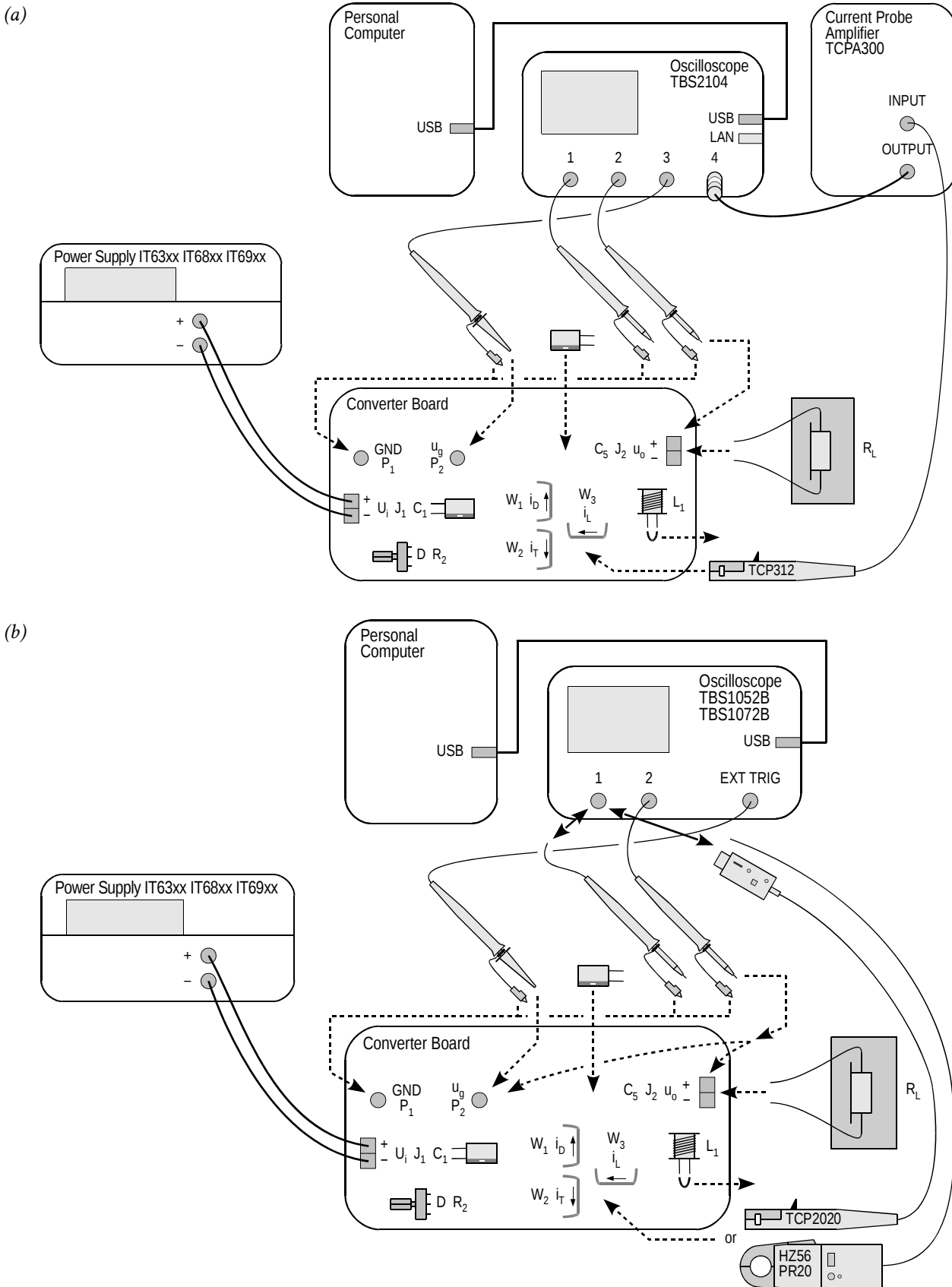


Fig. 2. Block diagram of the measurement set-up for recording time waveforms: (a) with a TBS2104 oscilloscope; (b) with a TBS1052B or TBS1072B oscilloscope

Read the contents of the following step in their entirety first and only then proceed with its execution.

- (e) using the knob, gradually increase the supply voltage to the nominal value of the input voltage U_i , watching that the current indicated by the power supply's ammeter does not significantly (by more than 50%) exceed the expected value as established in step 7; otherwise, deactivate the power supply's output with the *On/Off* button and verify your connections again.

Configuring the oscilloscope and generator

9. Using the oscilloscope communication software, upload initial settings to the oscilloscope:
- go to the *Get & Send Settings* tab;
 - click *Open* and read the file *ustawienia_3u_tbs2104 Ug_uo_il.set* or *ustawienia_3u_TBS1052B_Ug_uo.set*, as appropriate;
 - click *Send Settings*.

In the oscilloscope's screen, a stable, continuously refreshed pulse wave should be displayed, as attested, among others, by the message "Trig'd" (*Triggered*) appearing above the graticule. If this does not happen, ask the teacher to check oscilloscope settings.

10. In case of need, adjust:
- the time base and the trigger event position (*Horizontal Scale* and *Horizontal Position* knobs) so that 3 to 7 periods of the u_g voltage are visible; the trigger instant, indicated by an arrow at the top of the graticule, must appear within the screen, i.e. it cannot be located at either end of the graticule;
 - gain and zero level position (*Vertical Scale* and *Position* knobs) of the channel where the generator voltage is measured so that its waveform is easily observed, is located at the very bottom of the screen and extends vertically over approximately one division.
11. Using the potentiometer R_2 , using the *Pos Duty* or *Pos. Duty Cycle* measurement result displayed on the oscilloscope, coarsely set half of the expected nominal (i.e. one corresponding to the nominal input voltage U_i) duty cycle as calculated in Exercise 7K (Task 4).

Setting a duty cycle higher than the one indicated above at this moment may cause the transistor or the diode to be destroyed as a result of excessive power dissipation in the circuit where output passive components are absent. It will be only possible to increase the duty cycle at a specified moment after passive components are connected.

12. Bring the supply voltage down to zero.

Suppling the loaded circuit

13. To the converter's output (terminal block J_2), attach a load in the form of a resistor, or a set of resistors, having a resistance such that at the nominal output voltage U_o as assumed in design, the assumed nominal output current I_o is obtained, and having a resultant admissible power of at least twice the nominal output power of the converter.
14. Place the load on a heat resistant pad. Ensure that no component or wire touches the load; this equally applies to voltage and current probe cables. Otherwise, wire or termination insulation can melt.

The above conditions must be kept ensured over the entire course of this exercise!

Do not touch the load while realising this exercise, as, depending on operating conditions, its temperature can rise above 100 °C. Risk of burn!

15. Calculate the expected input current of the loaded converter for the duty cycle D set above, the nominal input voltage U_i and the resistance of the load used R_L (see Exercise 7K, Task 8).
16. On the power supply, push *I-Set* and set current limit to 3 A.

17. Push *V-Set* and gradually restore the nominal input voltage U_i , watching that the current does not significantly (by more than 20%) exceed the expected value as established in step 15; otherwise, de-activate the power supply's output with the *On/Off* button and verify the circuit again.

From this moment on, all until the completion of the exercise, under no circumstances should a different time base (*Horizontal Scale* knob) or trigger instant position (*Horizontal Position* knob) be set! This would cause de-synchronisation between consecutive oscilloscope images, thus rendering their analysis impossible at the result processing stage.

From this moment on, the duty cycle of the generator voltage (thus the setting of the potentiometer R_2) should not be changed unless you are explicitly told to! This would cause an inconsistency between consecutive oscilloscope images, thus rendering their analysis impossible at the result processing stage.

2.3. Converter component roles

Output voltage measurement with inductor and output capacitor absent

1. [TBS1052B, TBS1072B] Na oscyloskopie zachowaj obraz napięcia u_g :
 - (a) save the control voltage waveform u_g in the oscilloscope's memory:
 - push *Save Recall*,
 - using the appropriate button beside the screen, set *Action* to *Save Waveform*,
 - select saving to oscilloscope memory, *Save To: Ref*,
 - set *Source* to channel 1 (*CH1*),
 - select destination as Memory A, *To: Ref A*,
 - push *Save*;
 - (b) display the u_g waveform from the Memory A by pushing *R* and then, using an appropriate button beside the screen, set *Ref A* to *On*; as a result, the waveform observed previously should become duplicated in a different colour (this may be verified by slightly moving the waveform of channel 1 with the *Vertical Position* knob).
2. Set up output voltage measurement as the difference of output terminal voltages:
 - (a) [TBS1052B, TBS1072B] with the *Vertical Scale* knob, change the channel 1 gain to 5 V/div, then hide the channel 1 waveform with the *1* button;
 - (b) [TBS2104] with the buttons *1* and *2*, display channel 1 and 2 waveforms;
 - (c) with the *M* button, show the mathematical operation waveform and ensure that settings displayed in the right-hand side of the screen indicate that this waveform corresponds to the difference of channel 1 and 2 waveforms (*Ch1 – Ch2*);
 - (d) if necessary, set the scale of the mathematical operation waveform to 5 V/div by selecting *Vertical Scale* with an appropriate button beside the screen and set the value with the *Multipurpose* knob.
3. Attach the grounds of both voltage probes from channels 1 and 2 to the point P₁ (if this has not been already done). With the needle tips (after caps are taken off) of the channel 1 and 2 voltage probes, touch the terminals 1 and 2, respectively, of the terminal block J₂.
 In the screen, as the mathematical operation waveform M, the waveform of the converter's output voltage u_o should be displayed. Make sure that the sign of this voltage as measured conforms to the operating principle of the circuit under investigation.
4. Without modifying any settings in the circuit or on the oscilloscope, record the oscilloscope image of the waveforms u_g and u_o in a graphical form
 - in the OpenChoice Desktop application, go to the *Screen Capture* tab;
 - download the screen image to the computer by clicking *Get Screen*;
 - save the oscilloscope image in a graphical form by clicking *Save As*.
5. Disconnect channel 1 and 2 probes from the circuit.
6. Save the resulting ultimate oscilloscope settings for voltage measurements, to a file:
 - go to the *Get & Send Settings* tab;
 - click *Get Settings*;
 - click *Save As* and save the file in your team account.

Current measurement with inductor and output capacitor absent

7. [TBS1052B, TBS1072B] Modify the measurement set-up to enable currents to be measured:
 - (a) upload settings appropriate for current measurements to the oscilloscope:
 - click *Open* and read the file *ustawienia_3u_TBS1052B_il.set*,

- click *Send Settings*;
- (b) detach the voltage probe from channel 1 (without disconnecting it from the circuit);
 - (c) attach the current probe to channel 1 and configure this probe according to the instruction manual available at the laboratory stand.
8. [TBS2104] Set up current measurement:
- (a) attach the output of the current probe amplifier to channel 4 of the oscilloscope;
 - (b) switch the current probe amplifier on and set it up according to the instruction manual available at the laboratory stand, selecting a current-to-voltage conversion ratio appropriate for a current value equal to the output current assumed in design;
 - (c) on the oscilloscope, with buttons *1*, *2*, *M* and *4*, hide channel 1 and 2 waveforms as well as the mathematical operation waveform, and show the channel 4 waveform.
9. Clamp the probe on the wire conducting the current of the inductor (presently shorted) i_L (wire W_3) so that the positive current direction as indicated by an arrow on the probe body is in accordance with the arrow in Fig. 1. A waveform of the current i_L should be displayed on the oscilloscope. Make sure that the sign of the current as measured is positive, which indicates that the probe has been oriented correctly.
10. Supposing that the transistor is an ideal switch, estimate its expected on-state current, considering that the inductor L_1 and the capacitor C_5 are absent from the circuit (i.e., shorted or opened, respectively).
- Check whether the value indicated on the oscilloscope, according to the scale of the respective channel, conforms to this expectation. Otherwise, determine and eliminate the source of such a discrepancy (e.g. incorrectly calculated or applied load resistance, incorrect input or output voltage, incorrect current probe or oscilloscope settings).
11. Without modifying any settings in the circuit or on the oscilloscope, record an oscilloscope image of the u_g and i_L waveforms in a graphical form:
- in the OpenChoice Desktop application, go to the *Screen Capture* tab;
 - download the screen image to the computer by clicking *Get Screen*;
 - save the oscilloscope image in a graphical form by clicking *Save As*.
12. Save the resulting ultimate oscilloscope settings for current measurements, to a file:
- go to the *Get & Send Settings* tab;
 - click *Get Settings*;
 - click *Save As* and save the file in your team account.

Effect of passive components on circuit operation

13. Insert the inductor into the converter circuit:
- (a) bring the input voltage down to zero;
 - (b) unclamp the current probe from the wire;
 - (c) eliminate the short between the terminals of the inductor L_1 ;
 - (d) restore the nominal value of the input voltage U_i , watching that the expected input current still is not significantly exceeded;
 - (e) clamp the current probe back so that to measure the current i_L (wire W_3) considering its direction;
 - (f) verify that the direction (sign) of the current is correct as indicated on the oscilloscope.
14. Without modifying any settings in the circuit or on the oscilloscope, record an oscilloscope image of the u_g and i_L waveforms in a graphical form.
15. [TBS1052B, TBS1072B] Detach the current probe from channel 1 of the oscilloscope (without switching this probe off); and in its place, attach the voltage probe back.

16. Measure the output voltage:
 - (a) through the *Get & Send Settings* tab, from the file saved in step 6, read and upload the voltage measurement settings;
 - (b) with needle tips of the channel 1 and 2 voltage probes, touch the terminals 1 and 2, respectively, of the terminal block J₂;
 - (c) through the *Screen Capture* tab, record an oscilloscope image of the u_g and u_o waveforms in a graphical form.
17. Insert the output capacitor into the converter circuit:
 - (a) bring the input voltage down to zero;
 - (b) unclamp the current probe from the wire;
 - (c) at the appropriate location on the board, solder the capacitor C₅ minding its polarity;
 - (d) using a multimeter set to its circuit continuity test mode, make sure that the “+” terminal of the power supply is connected with the positive terminal of the capacitor C₅;
 - (e) restore the nominal value of the input voltage U_i , watching that the expected input current still is not significantly exceeded;
18. Without modifying any settings in the circuit or on the oscilloscope, record a new oscilloscope image of the u_g and u_o waveforms in a graphical form.
19. Put caps back to the tips of the channel 1 and 2 voltage probes.
20. [TBS1052B, TBS1072B] Detach the voltage probe from channel 1 of the oscilloscope; in its place, attach the current probe back.
21. Measure the inductor current:
 - (a) through the *Get & Send Settings* tab, from the file saved in step 12, read and upload the current measurement settings;
 - (b) clamp the current probe back so that to measure the current i_L (wire W₃) considering its direction
 - (c) verify that the direction (sign) of the current is correct as indicated on the oscilloscope;
 - (d) through the *Screen Capture* tab, record an oscilloscope image of the u_g and i_L waveforms in a graphical form.

Single-pole double-throw semiconductor switch

22. Move the current probe to the wire conducting the diode current i_D , minding its direction according to Fig. 1. Verify that the direction indicated on the oscilloscope is correct.
23. Without modifying any settings in the circuit or on the oscilloscope, record a new oscilloscope image of the u_g and i_D waveforms in a graphical form.
24. Move the current probe to the wire conducting the transistor current i_T , minding its direction according to Fig. 1. Verify that the direction indicated on the oscilloscope is correct.
25. Without modifying any settings in the circuit or on the oscilloscope, record a new oscilloscope image of the u_g and i_T waveforms in a graphical form.

2.4. Buck circuit as a converter of electrical energy

Waveforms under nominal conditions

1. By measuring the input voltage U_i with a multimeter in the terminal block J₁, ensure that its value is equal to the nominal one with an accuracy of ± 0.1 V.
2. Using the potentiometer R₂, modify the duty cycle so that to obtain the nominal value of the output voltage U_o as assumed in design with an accuracy of ± 0.1 V, by measuring this voltage with a multimeter in the terminal block J₂.
3. Move the current probe to the wire conducting the inductor current i_L , minding its direction according to Fig. 1. Verify that the direction indicated on the oscilloscope is correct.
4. Without modifying any settings in the circuit or on the oscilloscope, record a new oscilloscope image of the u_g and i_L waveforms in a graphical form.
5. [TBS1052B, TBS1072B] Detach the current probe from channel 1 of the oscilloscope (without switching this probe off); in its place, attach the voltage probe back.
6. Measure the output voltage:
 - (a) through the *Get & Send Settings* tab, from the file saved in step 6, read and upload the voltage measurement settings;
 - (b) with needle tips of the channel 1 and 2 voltage probes, touch the terminals 1 and 2, respectively, of the terminal block J₂;
 - (c) through the *Screen Capture* tab, record an oscilloscope image of the u_g and u_o waveforms in a graphical form.

Reconfiguring the measurement set-up

A block diagram of the measurement set-up is presented in Fig. 3. Connections to be made or modified, in the way described below, are marked in black, while grey lines show existing connections to be kept unchanged.

7. [TBS1052B, TBS1072B] Detach the voltage probe from channel 1 of the oscilloscope; in its place, attach the current probe back.
8. Set up transistor current measurement:
 - (a) move the current probe to the wire conducting the transistor current i_T , minding its direction according to Fig. 1; verify that the direction indicated on the oscilloscope is correct;
 - (b) through the *Get & Send Settings* tab, from the file saved in step 12, read and upload the current measurement settings;
 - (c) [TBS2104] activate the measurement of the duty cycle of the current:
 - push *Measure*;
 - with an appropriate button beside the screen, select *Ch3*, then with the *Multipurpose* knob, de-select the item *+Duty*;
 - with a button beside the screen, select *Ch4*, then with the *Multipurpose* knob, select the item *+Duty*;
 - close the menu with the *Menu On/Off* button.
9. Bring the input voltage down to zero.
10. Adapt the set-up for measuring the input and output currents:
 - (a) in series with the input, i.e. between the power supply and the terminal block J₁, and in series with the output, i.e. between the terminal block J₂ and the load, insert two multimeters of the same model in a way enabling currents to be measured up to the value expected for the output current, i.e. ensuring that appropriate sockets are used;

- (b) set the multimeters to the DC current measurement mode, considering the expected value as above.

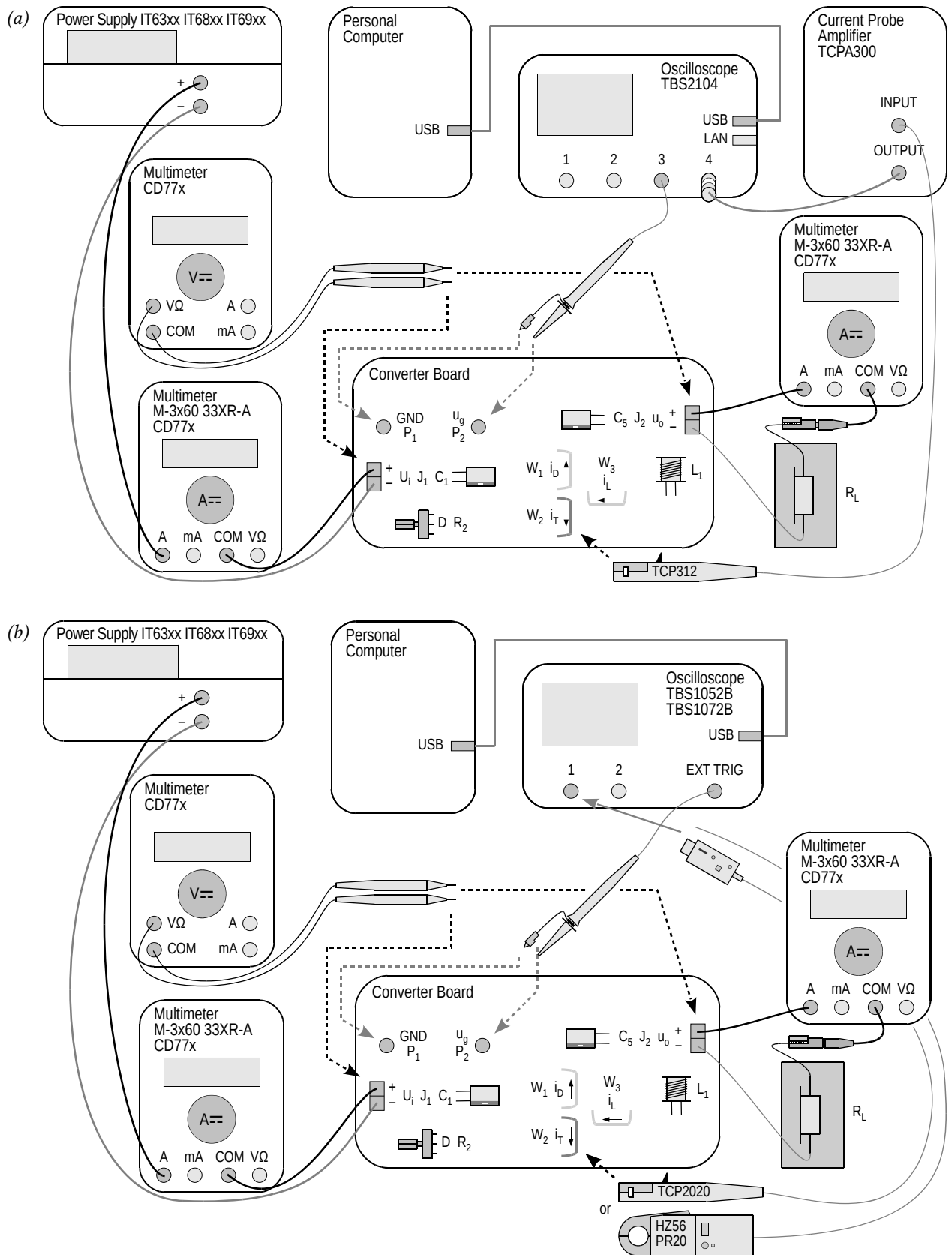


Fig. 3. Block diagram of the measurement set-up for measuring static characteristics: (a) with a TBS2104 oscilloscope; (b) with a TBS1052B or TBS1072B oscilloscope

Measuring static characteristics

Before continuing, the wiring of the multimeters must be verified by the teacher.

11. Restore the nominal input voltage.

During the execution of the following step, exceeding the value of 18 V during adjustment, even momentarily, may cause the integrated circuit U_1 to be damaged!

If a discharged battery indicator (battery symbol) shows up on the multimeter's display, do not go on with measurements, but inform the teacher in order to replace the battery. Otherwise multimeter indications may become erroneous.

12. For 5 to 10 measurement points defined by the value of the input voltage varied within the range determined in design, from the maximum towards the minimum (not in the opposite direction), among which values the nominal value assumed in design must appear:

- (a) on the power supply, set the selected input voltage;
- (b) with the potentiometer R_2 , set the duty cycle so that to obtain the nominal value of the output voltage U_o , by measuring the DC value of this voltage in the terminal block J_2 using a third multimeter;
- (c) from the oscilloscope, read out and write down the duty cycle of the transistor current D_{π} (*Pos Duty* or *Pos. Duty Cycle* indication);
- (d) from the multimeters, read out and write down DC values of the input current I_i and of the output current I_o ;
- (e) using the third multimeter, measure and write down the DC value of the input voltage U_i (at the terminal block J_i) and of the output voltage U_o (in the terminal block J_2).

2.5. Terminating measurements

1. Using the potentiometer R_2 , decrease the duty cycle to its minimum.
2. Bring the power supply voltage down to zero and de-activate its output with the *On/Off* button.
3. Switch the power supply off.
4. Detach the current probe from the circuit.
5. Switch the current probe off in a way appropriate for the model used.
6. [TBS2104] Do not disconnect the current probe from its amplifier or the probe amplifier from the oscilloscope.
[TBS1052B, TBS1072B] Disconnect the current probe from the oscilloscope.
7. Disconnect voltage probes from the circuit. Do not disconnect them, however, from the oscilloscope.
8. Disconnect the circuit from the power supply.
9. Disconnect the load from the circuit.

3. Processing and Analysing Results

3.1. Buck converter topology

Semiconductor switch

1. In Part 1 of the report, include oscilloscope images enabling waveforms of component currents and of the control voltage to be compared against each other: $\{u_g, i_L\}$, $\{u_g, i_D\}$ and $\{u_g, i_T\}$ as recorded in steps 2.3/21, 23 and 25, respectively.
2. Complete Part 1 of the report.

Circuit component roles

3. In Part 2 of the report, set together oscilloscope images recorded in Section 2.3: with the output passive components effectively eliminated (steps 4 and 11), after the short between the inductor's terminals was eliminated (steps 14 and 16) and after the output capacitor was soldered in (steps 18 and 21).
4. Fill in Part 2 of the report.

Operating parameters under nominal conditions

5. Fill in Part 3 of the report.

3.2. Circuit characteristics and effect of transistor

Efficiency

1. Based on your results of measurements performed in step 2.4/12, calculate for each measurement point (see Manual 7K, Sub-chapter 5.5):
 - (a) average input power P_i , from appropriate voltage and current measured (assuming that the input voltage is constant in time);
 - (b) average output power P_o , from appropriate voltage and current measured (assuming that the output voltage is constant in time);
 - (c) efficiency η , from its definition;
 - (d) voltage conversion ratio K_U , from its definition;
 - (e) * current conversion ratio K_I , defined as

$$K_I = \frac{I}{I_{g(0)}} \quad (3.1)$$

2. For each value of the duty cycle D_{IT} , calculate:
 - (a) voltage conversion ratio of an ideal (lossless) converter $K_{U(id)}$, from the analytical formula (see Manual 7K, Sub-chapter 5.2);
 - (b) the ratio of $K_U / K_{U(id)}$, based on your results from sub-steps (a) and 1(d).
3. Collect measurement and calculation results in appropriate tables in Part 4 of the report.
4. Complete Part 4 of the report.

Voltage conversion ratio

5. For a dense set of values of the duty cycle D_{IT} covering their entire possible range, i.e. [0; 1], so that it is later possible to plot a characteristic in the entire range of 0 to 1, making the impression of a smooth line, calculate again the voltage conversion ratio of an ideal converter $K_{U(id)}$ [see step 2(a)]. Put the values obtained in the appropriate table in Part 5 of the report.
6. Complete Part 5 of the report.

Input current

7. * For a dense set of values of the duty cycle D_{IT} covering their entire possible range, i.e. [0; 1], so that it is later possible to plot a characteristic in the entire range of 0 to 1, making the impression of a smooth line, calculate theoretical values of the current conversion ratio K_I by expressing the direct component of the input current $I_{g(0)}$ in the definition (3.1) as a function of the output current using the analytical formula (see 7K, Sub-chapter 5.5). Put the values obtained in the appropriate table in Part 6 of the report.
8. Fill in Part 6 of the report.

Transistor power loss minimisation

9. Fill in Part 7 of the report.

4. Required Knowledge

4.1. Prerequisites

- Buck converter operation (circuit without passive component, with the inductor, and with the output capacitor): electrical schematic, voltage and current waveforms and values with special emphasis on output voltage and input current (Manual 7K, Refs. B and C, Sections 5.2, 5.4 and 5.5)

4.2. Test scope

The problem scope related to this exercise is common with Exercise 7K; it has been given in Manual 7K.

5. References

- [1] Benda V., Gowar J., Grant D. A.: *Power Semiconductor Devices: Theory and Applications*. Wiley, 1999. ISBN 0-471-97644-X.
- [3] Erickson R. W., Maksimović D.: *Fundamentals of Power Electronics. Second Edition*. Springer, 2001. ISBN 0-792-37270-0.



POWER DEVICES AND SYSTEMS LABORATORY

Exercise 3U

Buck DC converter

Exercise and manual elaborated by
Łukasz Starzak

Łódź 2020

Contents

B Exercise Introduction	5
1. Exercise Aim and Plan.....	5
C Experiment.....	7
2. Measurements	7
2.1. Measurement set-up	7
2.2. Preparation for measurements.....	9
Configuring the measurement set-up	9
Supplying the unloaded circuit	9
Configuring the oscilloscope and generator	11
Supplying the loaded circuit	11
2.3. Converter component roles	13
Output voltage measurement without inductor and capacitor	13
Current measurement without inductor and capacitor.....	13
Effect of passive components on circuit operation.....	14
Single-pole double-throw semiconductor switch	15
2.4. Buck circuit as a converter of electrical energy.....	16
Waveforms under nominal conditions	16
Reconfiguring the measurement set-up.....	16
Measuring static characteristics.....	18
2.5. Terminating measurements.....	19
D Results	21
3. Processing and Analysing Results.....	21
3.1. Buck converter topology	21
Semiconductor switch	21
Circuit component roles	21
Operating parameters under nominal conditions.....	21
3.2. Circuit characteristics and effect of transistor	22
Efficiency	22
Voltage conversion ratio.....	22
Input current.....	22
Transistor power loss minimisation	22
E Information	23
4. Required Knowledge.....	23
4.1. Prerequisites	23
4.2. Test scope.....	23
5. References	23

Exercise Introduction

1. Exercise Aim and Plan

The aim of this exercise is to get acquainted with the operation of one of the most common power electronic converters: the DC converter, which at the same time is a typical application of the power MOSFET. In this specific case, the non-isolated (transformerless) step-down (buck) circuit will be investigated, which has the simplest topology and operating principle among DC converters. As in any DC converter, the transistor is there a component of a single-pole double-throw (SPDT) semiconductor switch whose role is to switch over a current from one branch to another one. Based on this example, the pulse width modulation (PWM) method of controlling power semiconductor devices will be illustrated.

This exercise demonstrates that the switched-mode technique using power transistors enables to accomplish useful functions in DC circuits while achieving high energy conversion efficiency. However, obtaining a functional circuit is impossible without using passive power components, whose role will also be experimentally investigated.

The DC converter designed and assembled in the frame of Exercise 7K will be the specific object of investigation. It is also in the manual for Exercise 7K that theoretical material necessary for carrying out this exercise has been provided or referenced.

2. Measurements

2.1. Measurement set-up

The schematic diagram of the non-isolated buck (step-down) converter has been presented in Fig. 1. Screw terminal blocks enable the connection of a **power supply** (terminal block J_1 , input voltage U_i) and of a **load** R_L (terminal block J_2 , output voltage u_o). It should be noted that the voltages U_i and u_o also appear across the capacitors C_1 and C_5 , respectively, that are polar components, which requires the correct polarity of the input voltage to be assured. To supply the circuit, any power supply with a current capability of at least 3 A, smoothly adjustable voltage and adjustable current limit can be used.

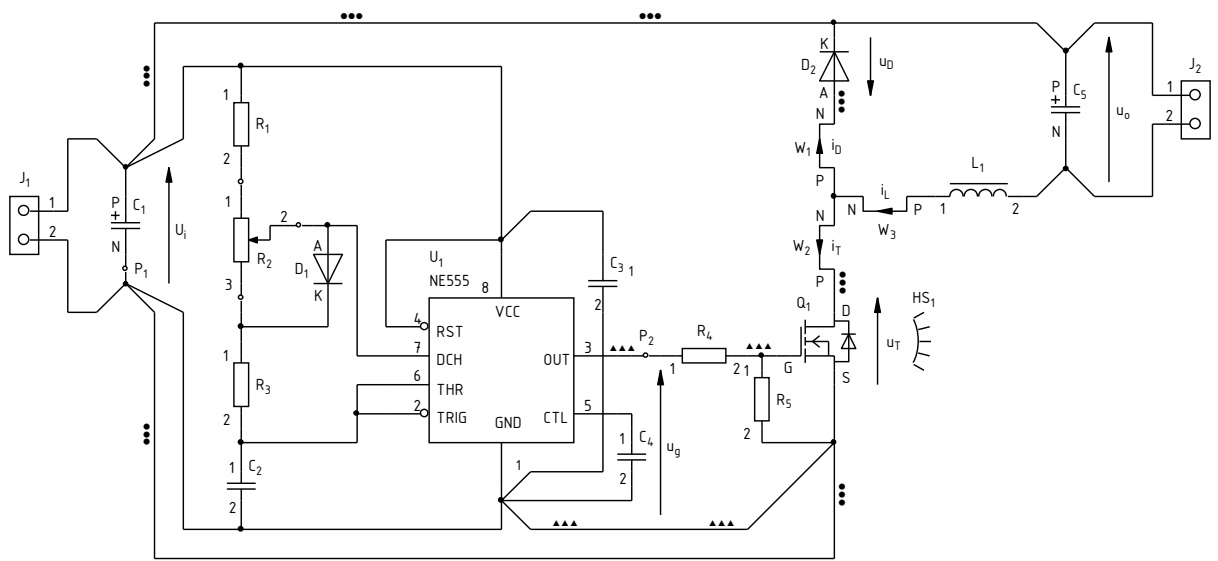


Fig. 1. Schematic diagram of the buck converter circuit under investigation

From among the **components of the power loop**, it will be the semiconductor switch, i.e. the transistor T and the diode D, as well as the output capacitor C_1 that will operate constantly. The inductor L_1 will initially be shorted whereas the output capacitor C_5 will be disconnected from the circuit (unmounted component or one terminal desoldered). These components will be restored to the circuit over the course of the exercise.

The **pulse wave** controlling the transistor u_g comes from an embedded generator. The potentiometer R_2 enables the duty cycle of this waveform to be set.

The measurement point P_1 , connected to the circuit's **ground**, will be used to attach voltage probe grounds. The measurement point P_2 enables the generator **voltage** to be measured. Other voltages will be measured at the J_1 and J_2 terminal blocks.

Observing **current** waveforms is possible by clamping a current probe around one of the wires led out of the board: W_1 for the diode current i_D , W_2 for the transistor current i_T or W_3 for the inductor current i_L .

Depending on the stand, a four-channel or a two-channel **oscilloscope** may be used. In the latter case, due to the limited number of channels, it will be necessary to switch over voltage and current probes, additionally using the external trigger input. Measurement procedures are described further in this manual, along with oscilloscope model designations when procedures differ.

2.2. Preparation for measurements

Configuring the measurement set-up

A simplified block diagram of the measurement set-up, including the two possible oscilloscope models is presented in Fig. 2. It should be assembled and configured in the way described below and in the specified sequence. If an oscilloscope model designation is given in a given step, then this step concerns this specific model, while it should not be carried out in case another model is used.

In order not to waste time, you should continue with following steps in parallel with step 1.

1. Switch the computer on. After logon completes, switch the oscilloscope on and, if necessary, set up its connection to the computer following a manual available at the laboratory stand.
2. In the converter board, keep the output capacitor C_5 disconnected and the inductor L_1 shorted. Keep the terminals of the block J_2 unoccupied.
3. Switch the power supply on without activating its output.
4. Connect the power supply's output with the converter's input (U_i voltage), i.e. with the terminal block J_1 , minding the polarity of the capacitor C_1 .
5. Using a multimeter set to its circuit continuity test mode, verify that the „+” terminal of the power supply is connected to the VCC pin (pin 8) of the integrated circuit U_1 and that its „-” terminal is connected to the GND pin (pin 1).
6. Attach the voltage probe or probes with a 1:10 attenuation, connected to the input or inputs of the oscilloscope, so as to measure the generator's output voltage u_g (measurement points P_1 and P_2), considering its direction according to Fig. 1:
 - [TBS2104] in channel 3;
 - [TBS1052B, TBS1072B] in the external trigger channel (*Ext Trig*) and in channel 1.

Voltage probe grounds (alligator clip connectors) are shorted together inside the oscilloscope and connected to the supply network protective earth. They must be therefore always connected to the same electric potential. Any other connection might result in current flowing through the oscilloscope, which would damage its input circuitry!

Supplying the unloaded circuit

7. Within your results of Exercise 7K (Task 7), check out the expected input current of an unloaded converter (or calculate it again as the sum of the maximum supply current of the integrated circuit U_1 according to its documentation and the maximum current of the generator's RC network as assumed in design.

While executing the following step, pay attention not to exceed the value of 18 V at any moment, as this might damage the integrated circuit U_1 .

8. Supply the unloaded converter:
 - (a) if a multi-channel power supply is used, select the channel used with the *Local/CH* button;
 - (b) push *I-Set* and set the current limit to 100 mA;
 - (c) push *V-Set* and set the voltage to 0 V;
 - (d) activate the output with the *On/Off* button and display embedded meter indications with the *Meter* button;

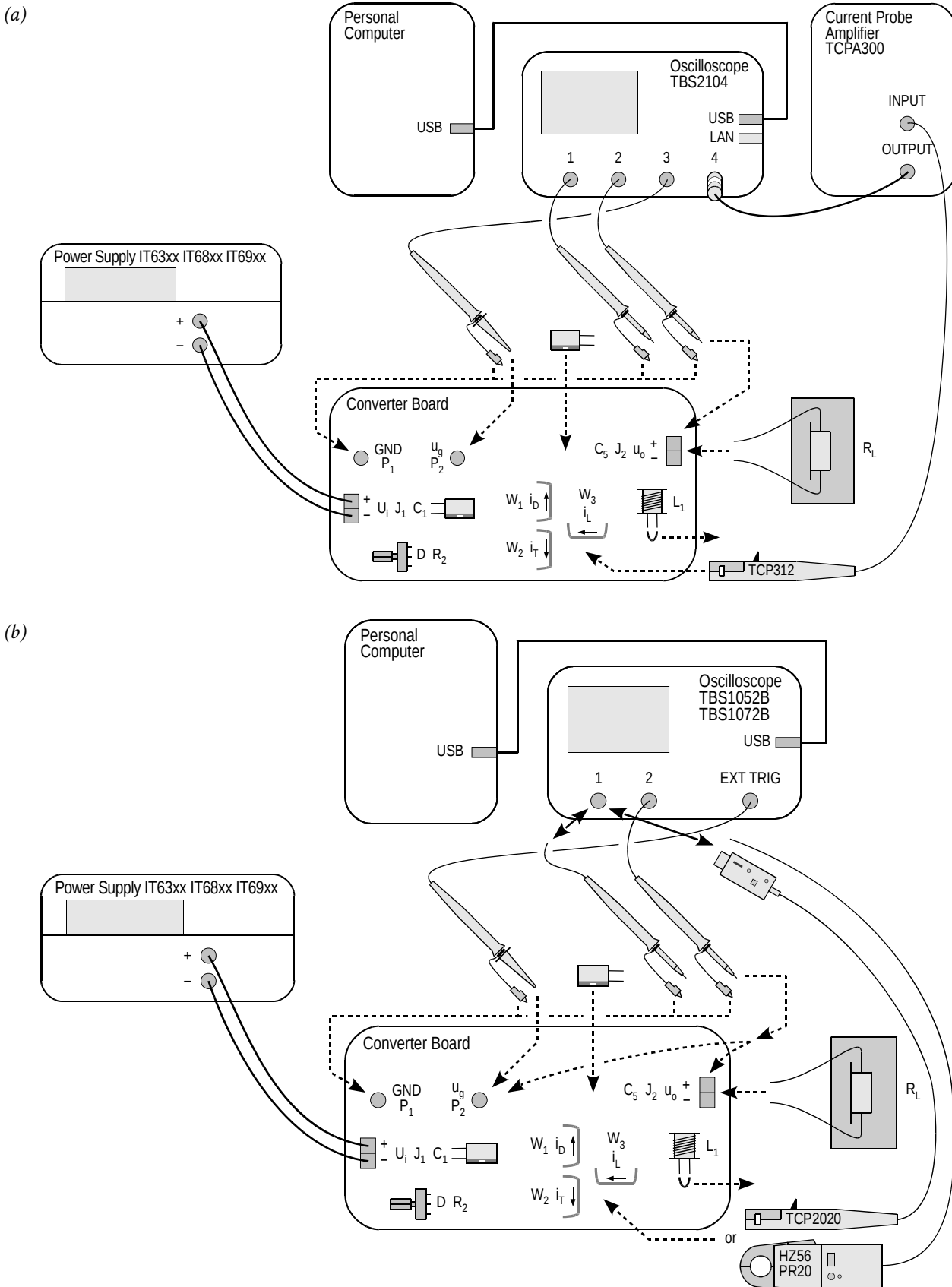


Fig. 2. Block diagram of the measurement set-up for recording time waveforms: (a) with a TBS2104 oscilloscope; (b) with a TBS1052B or TBS1072B oscilloscope

Read the contents of the following step in their entirety first and only then proceed with its execution.

- (e) using the knob, gradually increase the supply voltage to the nominal value of the input voltage U_i , watching that the current indicated by the power supply's ammeter does not significantly (by more than 50%) exceed the expected value as established in step 7; otherwise, deactivate the power supply's output with the *On/Off* button and verify your connections again.

Configuring the oscilloscope and generator

9. Using the oscilloscope communication software, upload initial settings to the oscilloscope:
- go to the *Get & Send Settings* tab;
 - click *Open* and read the file *ustawienia_3u_tbs2104 Ug_uo_il.set* or *ustawienia_3u_TBS1052B_Ug_uo.set*, as appropriate;
 - click *Send Settings*.

In the oscilloscope's screen, a stable, continuously refreshed pulse wave should be displayed, as attested, among others, by the message "Trig'd" (*Triggered*) appearing above the graticule. If this does not happen, ask the teacher to check oscilloscope settings.

10. In case of need, adjust:
- the time base and the trigger event position (*Horizontal Scale* and *Horizontal Position* knobs) so that 3 to 7 periods of the u_g voltage are visible; the trigger instant, indicated by an arrow at the top of the graticule, must appear within the screen, i.e. it cannot be located at either end of the graticule;
 - gain and zero level position (*Vertical Scale* and *Position* knobs) of the channel where the generator voltage is measured so that its waveform is easily observed, is located at the very bottom of the screen and extends vertically over approximately one division.
11. Using the potentiometer R_2 , using the *Pos Duty* or *Pos. Duty Cycle* measurement result displayed on the oscilloscope, coarsely set half of the expected nominal (i.e. one corresponding to the nominal input voltage U_i) duty cycle as calculated in Exercise 7K (Task 4).

Setting a duty cycle higher than the one indicated above at this moment may cause the transistor or the diode to be destroyed as a result of excessive power dissipation in the circuit where output passive components are absent. It will be only possible to increase the duty cycle at a specified moment after passive components are connected.

12. Bring the supply voltage down to zero.

Suppling the loaded circuit

13. To the converter's output (terminal block J_2), attach a load in the form of a resistor, or a set of resistors, having a resistance such that at the nominal output voltage U_o as assumed in design, the assumed nominal output current I_o is obtained, and having a resultant admissible power of at least twice the nominal output power of the converter.
14. Place the load on a heat resistant pad. Ensure that no component or wire touches the load; this equally applies to voltage and current probe cables. Otherwise, wire or termination insulation can melt.

The above conditions must be kept ensured over the entire course of this exercise!

Do not touch the load while realising this exercise, as, depending on operating conditions, its temperature can rise above 100 °C. Risk of burn!

15. Calculate the expected input current of the loaded converter for the duty cycle D set above, the nominal input voltage U_i and the resistance of the load used R_L (see Exercise 7K, Task 8).
16. On the power supply, push *I-Set* and set current limit to 3 A.

17. Push *V-Set* and gradually restore the nominal input voltage U_i , watching that the current does not significantly (by more than 20%) exceed the expected value as established in step 15; otherwise, de-activate the power supply's output with the *On/Off* button and verify the circuit again.

From this moment on, all until the completion of the exercise, under no circumstances should a different time base (*Horizontal Scale* knob) or trigger instant position (*Horizontal Position* knob) be set! This would cause de-synchronisation between consecutive oscilloscope images, thus rendering their analysis impossible at the result processing stage.

From this moment on, the duty cycle of the generator voltage (thus the setting of the potentiometer R_2) should not be changed unless you are explicitly told to! This would cause an inconsistency between consecutive oscilloscope images, thus rendering their analysis impossible at the result processing stage.

2.3. Converter component roles

Output voltage measurement with inductor and output capacitor absent

1. [TBS1052B, TBS1072B] Na oscyloskopie zachowaj obraz napięcia u_g :
 - (a) save the control voltage waveform u_g in the oscilloscope's memory:
 - push *Save Recall*,
 - using the appropriate button beside the screen, set *Action* to *Save Waveform*,
 - select saving to oscilloscope memory, *Save To: Ref*,
 - set *Source* to channel 1 (*CH1*),
 - select destination as Memory A, *To: Ref A*,
 - push *Save*;
 - (b) display the u_g waveform from the Memory A by pushing *R* and then, using an appropriate button beside the screen, set *Ref A* to *On*; as a result, the waveform observed previously should become duplicated in a different colour (this may be verified by slightly moving the waveform of channel 1 with the *Vertical Position* knob).
2. Set up output voltage measurement as the difference of output terminal voltages:
 - (a) [TBS1052B, TBS1072B] with the *Vertical Scale* knob, change the channel 1 gain to 5 V/div, then hide the channel 1 waveform with the *1* button;
 - (b) [TBS2104] with the buttons *1* and *2*, display channel 1 and 2 waveforms;
 - (c) with the *M* button, show the mathematical operation waveform and ensure that settings displayed in the right-hand side of the screen indicate that this waveform corresponds to the difference of channel 1 and 2 waveforms (*Ch1 – Ch2*);
 - (d) if necessary, set the scale of the mathematical operation waveform to 5 V/div by selecting *Vertical Scale* with an appropriate button beside the screen and set the value with the *Multipurpose* knob.
3. Attach the grounds of both voltage probes from channels 1 and 2 to the point P₁ (if this has not been already done). With the needle tips (after caps are taken off) of the channel 1 and 2 voltage probes, touch the terminals 1 and 2, respectively, of the terminal block J₂.
 In the screen, as the mathematical operation waveform M, the waveform of the converter's output voltage u_o should be displayed. Make sure that the sign of this voltage as measured conforms to the operating principle of the circuit under investigation.
4. Without modifying any settings in the circuit or on the oscilloscope, record the oscilloscope image of the waveforms u_g and u_o in a graphical form
 - in the OpenChoice Desktop application, go to the *Screen Capture* tab;
 - download the screen image to the computer by clicking *Get Screen*;
 - save the oscilloscope image in a graphical form by clicking *Save As*.
5. Disconnect channel 1 and 2 probes from the circuit.
6. Save the resulting ultimate oscilloscope settings for voltage measurements, to a file:
 - go to the *Get & Send Settings* tab;
 - click *Get Settings*;
 - click *Save As* and save the file in your team account.

Current measurement with inductor and output capacitor absent

7. [TBS1052B, TBS1072B] Modify the measurement set-up to enable currents to be measured:
 - (a) upload settings appropriate for current measurements to the oscilloscope:
 - click *Open* and read the file *ustawienia_3u_TBS1052B_il.set*,

- click *Send Settings*;
- (b) detach the voltage probe from channel 1 (without disconnecting it from the circuit);
 - (c) attach the current probe to channel 1 and configure this probe according to the instruction manual available at the laboratory stand.
8. [TBS2104] Set up current measurement:
- (a) attach the output of the current probe amplifier to channel 4 of the oscilloscope;
 - (b) switch the current probe amplifier on and set it up according to the instruction manual available at the laboratory stand, selecting a current-to-voltage conversion ratio appropriate for a current value equal to the output current assumed in design;
 - (c) on the oscilloscope, with buttons *1*, *2*, *M* and *4*, hide channel 1 and 2 waveforms as well as the mathematical operation waveform, and show the channel 4 waveform.
9. Clamp the probe on the wire conducting the current of the inductor (presently shorted) i_L (wire W_3) so that the positive current direction as indicated by an arrow on the probe body is in accordance with the arrow in Fig. 1. A waveform of the current i_L should be displayed on the oscilloscope. Make sure that the sign of the current as measured is positive, which indicates that the probe has been oriented correctly.
10. Supposing that the transistor is an ideal switch, estimate its expected on-state current, considering that the inductor L_1 and the capacitor C_5 are absent from the circuit (i.e., shorted or opened, respectively).
- Check whether the value indicated on the oscilloscope, according to the scale of the respective channel, conforms to this expectation. Otherwise, determine and eliminate the source of such a discrepancy (e.g. incorrectly calculated or applied load resistance, incorrect input or output voltage, incorrect current probe or oscilloscope settings).
11. Without modifying any settings in the circuit or on the oscilloscope, record an oscilloscope image of the u_g and i_L waveforms in a graphical form:
- in the OpenChoice Desktop application, go to the *Screen Capture* tab;
 - download the screen image to the computer by clicking *Get Screen*;
 - save the oscilloscope image in a graphical form by clicking *Save As*.
12. Save the resulting ultimate oscilloscope settings for current measurements, to a file:
- go to the *Get & Send Settings* tab;
 - click *Get Settings*;
 - click *Save As* and save the file in your team account.

Effect of passive components on circuit operation

13. Insert the inductor into the converter circuit:
- (a) bring the input voltage down to zero;
 - (b) unclamp the current probe from the wire;
 - (c) eliminate the short between the terminals of the inductor L_1 ;
 - (d) restore the nominal value of the input voltage U_i , watching that the expected input current still is not significantly exceeded;
 - (e) clamp the current probe back so that to measure the current i_L (wire W_3) considering its direction;
 - (f) verify that the direction (sign) of the current is correct as indicated on the oscilloscope.
14. Without modifying any settings in the circuit or on the oscilloscope, record an oscilloscope image of the u_g and i_L waveforms in a graphical form.
15. [TBS1052B, TBS1072B] Detach the current probe from channel 1 of the oscilloscope (without switching this probe off); and in its place, attach the voltage probe back.

16. Measure the output voltage:
 - (a) through the *Get & Send Settings* tab, from the file saved in step 6, read and upload the voltage measurement settings;
 - (b) with needle tips of the channel 1 and 2 voltage probes, touch the terminals 1 and 2, respectively, of the terminal block J₂;
 - (c) through the *Screen Capture* tab, record an oscilloscope image of the u_g and u_o waveforms in a graphical form.
17. Insert the output capacitor into the converter circuit:
 - (a) bring the input voltage down to zero;
 - (b) unclamp the current probe from the wire;
 - (c) at the appropriate location on the board, solder the capacitor C₅ minding its polarity;
 - (d) using a multimeter set to its circuit continuity test mode, make sure that the “+” terminal of the power supply is connected with the positive terminal of the capacitor C₅;
 - (e) restore the nominal value of the input voltage U_i , watching that the expected input current still is not significantly exceeded;
18. Without modifying any settings in the circuit or on the oscilloscope, record a new oscilloscope image of the u_g and u_o waveforms in a graphical form.
19. Put caps back to the tips of the channel 1 and 2 voltage probes.
20. [TBS1052B, TBS1072B] Detach the voltage probe from channel 1 of the oscilloscope; in its place, attach the current probe back.
21. Measure the inductor current:
 - (a) through the *Get & Send Settings* tab, from the file saved in step 12, read and upload the current measurement settings;
 - (b) clamp the current probe back so that to measure the current i_L (wire W₃) considering its direction
 - (c) verify that the direction (sign) of the current is correct as indicated on the oscilloscope;
 - (d) through the *Screen Capture* tab, record an oscilloscope image of the u_g and i_L waveforms in a graphical form.

Single-pole double-throw semiconductor switch

22. Move the current probe to the wire conducting the diode current i_D , minding its direction according to Fig. 1. Verify that the direction indicated on the oscilloscope is correct.
23. Without modifying any settings in the circuit or on the oscilloscope, record a new oscilloscope image of the u_g and i_D waveforms in a graphical form.
24. Move the current probe to the wire conducting the transistor current i_T , minding its direction according to Fig. 1. Verify that the direction indicated on the oscilloscope is correct.
25. Without modifying any settings in the circuit or on the oscilloscope, record a new oscilloscope image of the u_g and i_T waveforms in a graphical form.

2.4. Buck circuit as a converter of electrical energy

Waveforms under nominal conditions

1. By measuring the input voltage U_i with a multimeter in the terminal block J₁, ensure that its value is equal to the nominal one with an accuracy of ± 0.1 V.
2. Using the potentiometer R₂, modify the duty cycle so that to obtain the nominal value of the output voltage U_o as assumed in design with an accuracy of ± 0.1 V, by measuring this voltage with a multimeter in the terminal block J₂.
3. Move the current probe to the wire conducting the inductor current i_L , minding its direction according to Fig. 1. Verify that the direction indicated on the oscilloscope is correct.
4. Without modifying any settings in the circuit or on the oscilloscope, record a new oscilloscope image of the u_g and i_L waveforms in a graphical form.
5. [TBS1052B, TBS1072B] Detach the current probe from channel 1 of the oscilloscope (without switching this probe off); in its place, attach the voltage probe back.
6. Measure the output voltage:
 - (a) through the *Get & Send Settings* tab, from the file saved in step 6, read and upload the voltage measurement settings;
 - (b) with needle tips of the channel 1 and 2 voltage probes, touch the terminals 1 and 2, respectively, of the terminal block J₂;
 - (c) through the *Screen Capture* tab, record an oscilloscope image of the u_g and u_o waveforms in a graphical form.

Reconfiguring the measurement set-up

A block diagram of the measurement set-up is presented in Fig. 3. Connections to be made or modified, in the way described below, are marked in black, while grey lines show existing connections to be kept unchanged.

7. [TBS1052B, TBS1072B] Detach the voltage probe from channel 1 of the oscilloscope; in its place, attach the current probe back.
8. Set up transistor current measurement:
 - (a) move the current probe to the wire conducting the transistor current i_T , minding its direction according to Fig. 1; verify that the direction indicated on the oscilloscope is correct;
 - (b) through the *Get & Send Settings* tab, from the file saved in step 12, read and upload the current measurement settings;
 - (c) [TBS2104] activate the measurement of the duty cycle of the current:
 - push *Measure*;
 - with an appropriate button beside the screen, select *Ch3*, then with the *Multipurpose* knob, de-select the item *+Duty*;
 - with a button beside the screen, select *Ch4*, then with the *Multipurpose* knob, select the item *+Duty*;
 - close the menu with the *Menu On/Off* button.
9. Bring the input voltage down to zero.
10. Adapt the set-up for measuring the input and output currents:
 - (a) in series with the input, i.e. between the power supply and the terminal block J₁, and in series with the output, i.e. between the terminal block J₂ and the load, insert two multimeters of the same model in a way enabling currents to be measured up to the value expected for the output current, i.e. ensuring that appropriate sockets are used;

- (b) set the multimeters to the DC current measurement mode, considering the expected value as above.

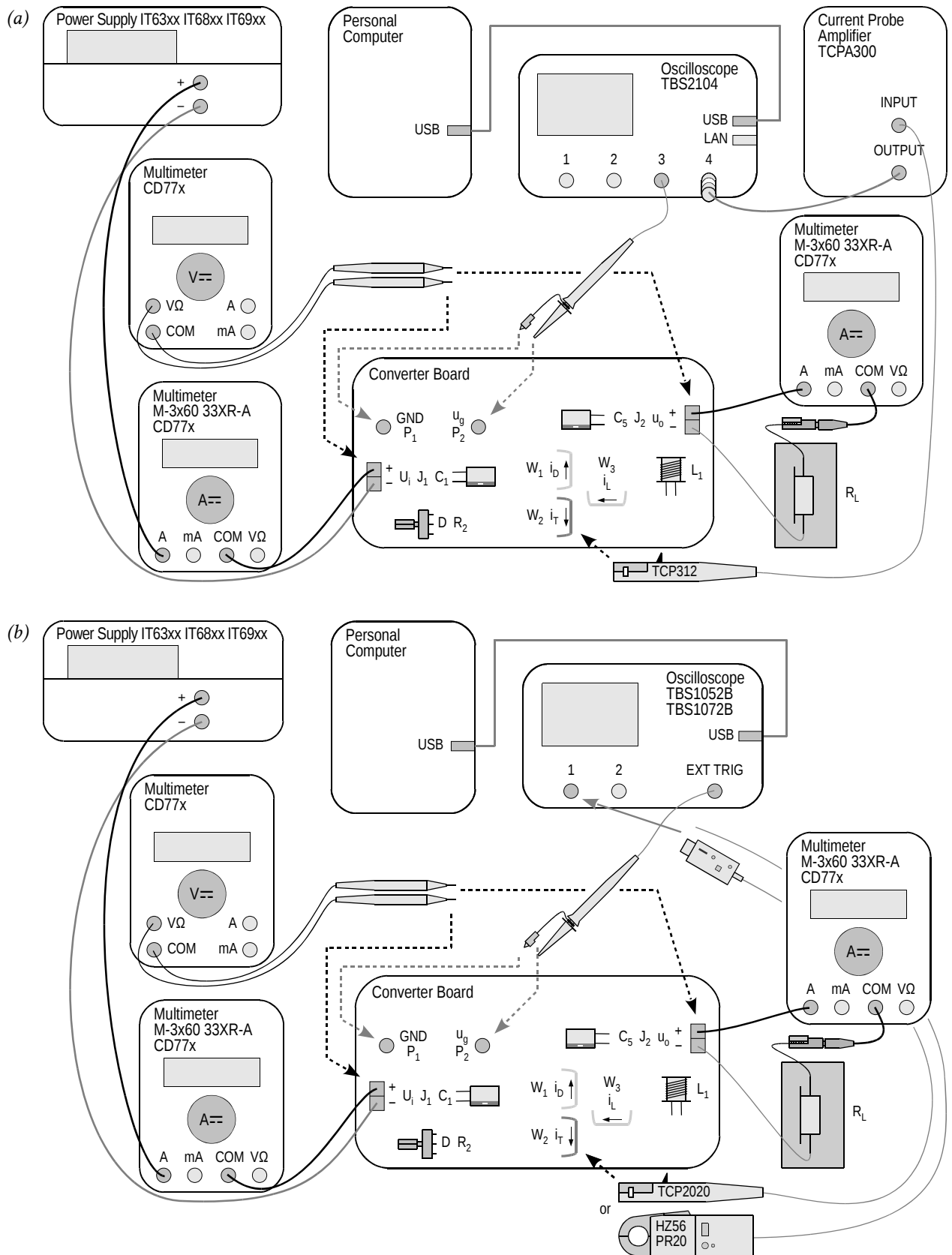


Fig. 3. Block diagram of the measurement set-up for measuring static characteristics: (a) with a TBS2104 oscilloscope; (b) with a TBS1052B or TBS1072B oscilloscope

Measuring static characteristics

Before continuing, the wiring of the multimeters must be verified by the teacher.

11. Restore the nominal input voltage.

During the execution of the following step, exceeding the value of 18 V during adjustment, even momentarily, may cause the integrated circuit U_1 to be damaged!

If a discharged battery indicator (battery symbol) shows up on the multimeter's display, do not go on with measurements, but inform the teacher in order to replace the battery. Otherwise multimeter indications may become erroneous.

12. For 5 to 10 measurement points defined by the value of the input voltage varied within the range determined in design, from the maximum towards the minimum (not in the opposite direction), among which values the nominal value assumed in design must appear:

- (a) on the power supply, set the selected input voltage;
- (b) with the potentiometer R_2 , set the duty cycle so that to obtain the nominal value of the output voltage U_o , by measuring the DC value of this voltage in the terminal block J_2 using a third multimeter;
- (c) from the oscilloscope, read out and write down the duty cycle of the transistor current D_{π} (*Pos Duty* or *Pos. Duty Cycle* indication);
- (d) from the multimeters, read out and write down DC values of the input current I_i and of the output current I_o ;
- (e) using the third multimeter, measure and write down the DC value of the input voltage U_i (at the terminal block J_i) and of the output voltage U_o (in the terminal block J_2).

2.5. Terminating measurements

1. Using the potentiometer R_2 , decrease the duty cycle to its minimum.
2. Bring the power supply voltage down to zero and de-activate its output with the *On/Off* button.
3. Switch the power supply off.
4. Detach the current probe from the circuit.
5. Switch the current probe off in a way appropriate for the model used.
6. [TBS2104] Do not disconnect the current probe from its amplifier or the probe amplifier from the oscilloscope.
[TBS1052B, TBS1072B] Disconnect the current probe from the oscilloscope.
7. Disconnect voltage probes from the circuit. Do not disconnect them, however, from the oscilloscope.
8. Disconnect the circuit from the power supply.
9. Disconnect the load from the circuit.

3. Processing and Analysing Results

3.1. Buck converter topology

Semiconductor switch

1. In Part 1 of the report, include oscilloscope images enabling waveforms of component currents and of the control voltage to be compared against each other: $\{u_g, i_L\}$, $\{u_g, i_D\}$ and $\{u_g, i_T\}$ as recorded in steps 2.3/21, 23 and 25, respectively.
2. Complete Part 1 of the report.

Circuit component roles

3. In Part 2 of the report, set together oscilloscope images recorded in Section 2.3: with the output passive components effectively eliminated (steps 4 and 11), after the short between the inductor's terminals was eliminated (steps 14 and 16) and after the output capacitor was soldered in (steps 18 and 21).
4. Fill in Part 2 of the report.

Operating parameters under nominal conditions

5. Fill in Part 3 of the report.

3.2. Circuit characteristics and effect of transistor

Efficiency

1. Based on your results of measurements performed in step 2.4/12, calculate for each measurement point (see Manual 7K, Sub-chapter 5.5):
 - (a) average input power P_i , from appropriate voltage and current measured (assuming that the input voltage is constant in time);
 - (b) average output power P_o , from appropriate voltage and current measured (assuming that the output voltage is constant in time);
 - (c) efficiency η , from its definition;
 - (d) voltage conversion ratio K_U , from its definition;
 - (e) * current conversion ratio K_I , defined as

$$K_I = \frac{I}{I_{g(0)}} \quad (3.1)$$

2. For each value of the duty cycle D_{IT} , calculate:
 - (a) voltage conversion ratio of an ideal (lossless) converter $K_{U(id)}$, from the analytical formula (see Manual 7K, Sub-chapter 5.2);
 - (b) the ratio of $K_U / K_{U(id)}$, based on your results from sub-steps (a) and 1(d).
3. Collect measurement and calculation results in appropriate tables in Part 4 of the report.
4. Complete Part 4 of the report.

Voltage conversion ratio

5. For a dense set of values of the duty cycle D_{IT} covering their entire possible range, i.e. [0; 1], so that it is later possible to plot a characteristic in the entire range of 0 to 1, making the impression of a smooth line, calculate again the voltage conversion ratio of an ideal converter $K_{U(id)}$ [see step 2(a)]. Put the values obtained in the appropriate table in Part 5 of the report.
6. Complete Part 5 of the report.

Input current

7. * For a dense set of values of the duty cycle D_{IT} covering their entire possible range, i.e. [0; 1], so that it is later possible to plot a characteristic in the entire range of 0 to 1, making the impression of a smooth line, calculate theoretical values of the current conversion ratio K_I by expressing the direct component of the input current $I_{g(0)}$ in the definition (3.1) as a function of the output current using the analytical formula (see 7K, Sub-chapter 5.5). Put the values obtained in the appropriate table in Part 6 of the report.
8. Fill in Part 6 of the report.

Transistor power loss minimisation

9. Fill in Part 7 of the report.

4. Required Knowledge

4.1. Prerequisites

- Buck converter operation (circuit without passive component, with the inductor, and with the output capacitor): electrical schematic, voltage and current waveforms and values with special emphasis on output voltage and input current (Manual 7K, Refs. B and C, Sections 5.2, 5.4 and 5.5)

4.2. Test scope

The problem scope related to this exercise is common with Exercise 7K; it has been given in Manual 7K.

5. References

- [1] Benda V., Gowar J., Grant D. A.: *Power Semiconductor Devices: Theory and Applications*. Wiley, 1999. ISBN 0-471-97644-X.
- [3] Erickson R. W., Maksimović D.: *Fundamentals of Power Electronics. Second Edition*. Springer, 2001. ISBN 0-792-37270-0.



POWER DEVICES AND SYSTEMS LABORATORY

Exercise 3U

Buck DC converter

Exercise and manual elaborated by
Łukasz Starzak

Łódź 2020

Contents

B Exercise Introduction	5
1. Exercise Aim and Plan.....	5
C Experiment.....	7
2. Measurements	7
2.1. Measurement set-up	7
2.2. Preparation for measurements.....	9
Configuring the measurement set-up	9
Supplying the unloaded circuit	9
Configuring the oscilloscope and generator	11
Supplying the loaded circuit	11
2.3. Converter component roles	13
Output voltage measurement without inductor and capacitor	13
Current measurement without inductor and capacitor.....	13
Effect of passive components on circuit operation.....	14
Single-pole double-throw semiconductor switch	15
2.4. Buck circuit as a converter of electrical energy.....	16
Waveforms under nominal conditions	16
Reconfiguring the measurement set-up.....	16
Measuring static characteristics.....	18
2.5. Terminating measurements.....	19
D Results	21
3. Processing and Analysing Results.....	21
3.1. Buck converter topology	21
Semiconductor switch	21
Circuit component roles	21
Operating parameters under nominal conditions.....	21
3.2. Circuit characteristics and effect of transistor	22
Efficiency	22
Voltage conversion ratio.....	22
Input current.....	22
Transistor power loss minimisation	22
E Information	23
4. Required Knowledge.....	23
4.1. Prerequisites	23
4.2. Test scope.....	23
5. References	23

Exercise Introduction

1. Exercise Aim and Plan

The aim of this exercise is to get acquainted with the operation of one of the most common power electronic converters: the DC converter, which at the same time is a typical application of the power MOSFET. In this specific case, the non-isolated (transformerless) step-down (buck) circuit will be investigated, which has the simplest topology and operating principle among DC converters. As in any DC converter, the transistor is there a component of a single-pole double-throw (SPDT) semiconductor switch whose role is to switch over a current from one branch to another one. Based on this example, the pulse width modulation (PWM) method of controlling power semiconductor devices will be illustrated.

This exercise demonstrates that the switched-mode technique using power transistors enables to accomplish useful functions in DC circuits while achieving high energy conversion efficiency. However, obtaining a functional circuit is impossible without using passive power components, whose role will also be experimentally investigated.

The DC converter designed and assembled in the frame of Exercise 7K will be the specific object of investigation. It is also in the manual for Exercise 7K that theoretical material necessary for carrying out this exercise has been provided or referenced.

From among the **components of the power loop**, it will be the semiconductor switch, i.e. the transistor T and the diode D, as well as the output capacitor C_1 that will operate constantly. The inductor L_1 will initially be shorted whereas the output capacitor C_5 will be disconnected from the circuit (unmounted component or one terminal desoldered). These components will be restored to the circuit over the course of the exercise.

The **pulse wave** controlling the transistor u_g comes from an embedded generator. The potentiometer R_2 enables the duty cycle of this waveform to be set.

The measurement point P_1 , connected to the circuit's **ground**, will be used to attach voltage probe grounds. The measurement point P_2 enables the generator **voltage** to be measured. Other voltages will be measured at the J_1 and J_2 terminal blocks.

Observing **current** waveforms is possible by clamping a current probe around one of the wires led out of the board: W_1 for the diode current i_D , W_2 for the transistor current i_T or W_3 for the inductor current i_L .

Depending on the stand, a four-channel or a two-channel **oscilloscope** may be used. In the latter case, due to the limited number of channels, it will be necessary to switch over voltage and current probes, additionally using the external trigger input. Measurement procedures are described further in this manual, along with oscilloscope model designations when procedures differ.

2.2. Preparation for measurements

Configuring the measurement set-up

A simplified block diagram of the measurement set-up, including the two possible oscilloscope models is presented in Fig. 2. It should be assembled and configured in the way described below and in the specified sequence. If an oscilloscope model designation is given in a given step, then this step concerns this specific model, while it should not be carried out in case another model is used.

In order not to waste time, you should continue with following steps in parallel with step 1.

1. Switch the computer on. After logon completes, switch the oscilloscope on and, if necessary, set up its connection to the computer following a manual available at the laboratory stand.
2. In the converter board, keep the output capacitor C_5 disconnected and the inductor L_1 shorted. Keep the terminals of the block J_2 unoccupied.
3. Switch the power supply on without activating its output.
4. Connect the power supply's output with the converter's input (U_i voltage), i.e. with the terminal block J_1 , minding the polarity of the capacitor C_1 .
5. Using a multimeter set to its circuit continuity test mode, verify that the „+” terminal of the power supply is connected to the VCC pin (pin 8) of the integrated circuit U_1 and that its „-” terminal is connected to the GND pin (pin 1).
6. Attach the voltage probe or probes with a 1:10 attenuation, connected to the input or inputs of the oscilloscope, so as to measure the generator's output voltage u_g (measurement points P_1 and P_2), considering its direction according to Fig. 1:
 - [TBS2104] in channel 3;
 - [TBS1052B, TBS1072B] in the external trigger channel (*Ext Trig*) and in channel 1.

Voltage probe grounds (alligator clip connectors) are shorted together inside the oscilloscope and connected to the supply network protective earth. They must be therefore always connected to the same electric potential. Any other connection might result in current flowing through the oscilloscope, which would damage its input circuitry!

Supplying the unloaded circuit

7. Within your results of Exercise 7K (Task 7), check out the expected input current of an unloaded converter (or calculate it again as the sum of the maximum supply current of the integrated circuit U_1 according to its documentation and the maximum current of the generator's RC network as assumed in design.

While executing the following step, pay attention not to exceed the value of 18 V at any moment, as this might damage the integrated circuit U_1 .

8. Supply the unloaded converter:
 - (a) if a multi-channel power supply is used, select the channel used with the *Local/CH* button;
 - (b) push *I-Set* and set the current limit to 100 mA;
 - (c) push *V-Set* and set the voltage to 0 V;
 - (d) activate the output with the *On/Off* button and display embedded meter indications with the *Meter* button;

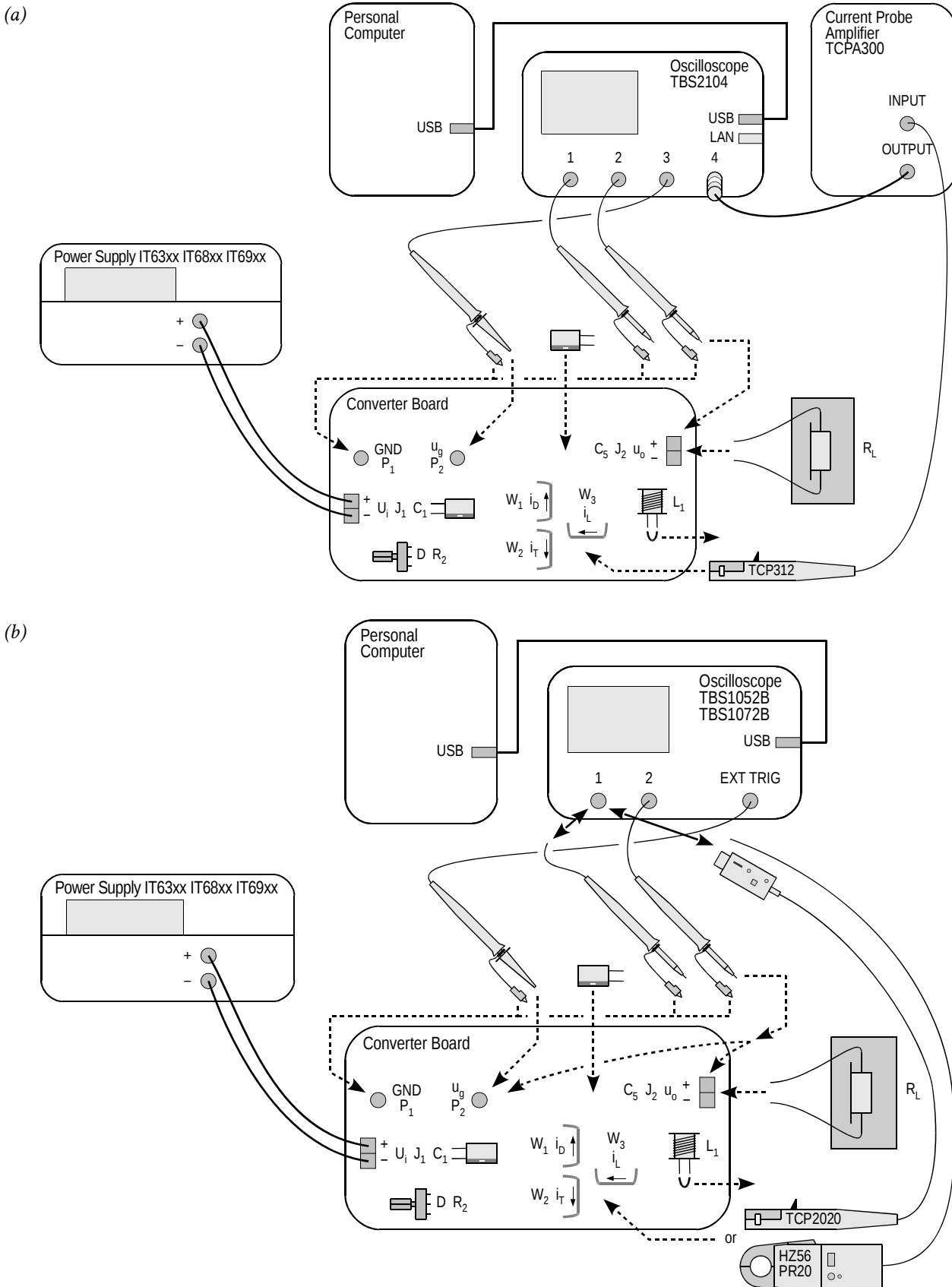


Fig. 2. Block diagram of the measurement set-up for recording time waveforms: (a) with a TBS2104 oscilloscope; (b) with a TBS1052B or TBS1072B oscilloscope

Read the contents of the following step in their entirety first and only then proceed with its execution.

- (e) using the knob, gradually increase the supply voltage to the nominal value of the input voltage U_i , watching that the current indicated by the power supply's ammeter does not significantly (by more than 50%) exceed the expected value as established in step 7; otherwise, deactivate the power supply's output with the *On/Off* button and verify your connections again.

Configuring the oscilloscope and generator

9. Using the oscilloscope communication software, upload initial settings to the oscilloscope:
- go to the *Get & Send Settings* tab;
 - click *Open* and read the file *ustawienia_3u_tbs2104 Ug_uo_il.set* or *ustawienia_3u_TBS1052B_Ug_uo.set*, as appropriate;
 - click *Send Settings*.

In the oscilloscope's screen, a stable, continuously refreshed pulse wave should be displayed, as attested, among others, by the message "Trig'd" (*Triggered*) appearing above the graticule. If this does not happen, ask the teacher to check oscilloscope settings.

10. In case of need, adjust:
- the time base and the trigger event position (*Horizontal Scale* and *Horizontal Position* knobs) so that 3 to 7 periods of the u_g voltage are visible; the trigger instant, indicated by an arrow at the top of the graticule, must appear within the screen, i.e. it cannot be located at either end of the graticule;
 - gain and zero level position (*Vertical Scale* and *Position* knobs) of the channel where the generator voltage is measured so that its waveform is easily observed, is located at the very bottom of the screen and extends vertically over approximately one division.
11. Using the potentiometer R_2 , using the *Pos Duty* or *Pos. Duty Cycle* measurement result displayed on the oscilloscope, coarsely set half of the expected nominal (i.e. one corresponding to the nominal input voltage U_i) duty cycle as calculated in Exercise 7K (Task 4).

Setting a duty cycle higher than the one indicated above at this moment may cause the transistor or the diode to be destroyed as a result of excessive power dissipation in the circuit where output passive components are absent. It will be only possible to increase the duty cycle at a specified moment after passive components are connected.

12. Bring the supply voltage down to zero.

Suppling the loaded circuit

13. To the converter's output (terminal block J_2), attach a load in the form of a resistor, or a set of resistors, having a resistance such that at the nominal output voltage U_o as assumed in design, the assumed nominal output current I_o is obtained, and having a resultant admissible power of at least twice the nominal output power of the converter.
14. Place the load on a heat resistant pad. Ensure that no component or wire touches the load; this equally applies to voltage and current probe cables. Otherwise, wire or termination insulation can melt.

The above conditions must be kept ensured over the entire course of this exercise!

Do not touch the load while realising this exercise, as, depending on operating conditions, its temperature can rise above 100 °C. Risk of burn!

15. Calculate the expected input current of the loaded converter for the duty cycle D set above, the nominal input voltage U_i and the resistance of the load used R_L (see Exercise 7K, Task 8).
16. On the power supply, push *I-Set* and set current limit to 3 A.

17. Push *V-Set* and gradually restore the nominal input voltage U_i , watching that the current does not significantly (by more than 20%) exceed the expected value as established in step 15; otherwise, de-activate the power supply's output with the *On/Off* button and verify the circuit again.

From this moment on, all until the completion of the exercise, under no circumstances should a different time base (*Horizontal Scale* knob) or trigger instant position (*Horizontal Position* knob) be set! This would cause de-synchronisation between consecutive oscilloscope images, thus rendering their analysis impossible at the result processing stage.

From this moment on, the duty cycle of the generator voltage (thus the setting of the potentiometer R_2) should not be changed unless you are explicitly told to! This would cause an inconsistency between consecutive oscilloscope images, thus rendering their analysis impossible at the result processing stage.

2.3. Converter component roles

Output voltage measurement with inductor and output capacitor absent

1. [TBS1052B, TBS1072B] Na oscyloskopie zachowaj obraz napięcia u_g :
 - (a) save the control voltage waveform u_g in the oscilloscope's memory:
 - push *Save Recall*,
 - using the appropriate button beside the screen, set *Action* to *Save Waveform*,
 - select saving to oscilloscope memory, *Save To: Ref*,
 - set *Source* to channel 1 (*CH1*),
 - select destination as Memory A, *To: Ref A*,
 - push *Save*;
 - (b) display the u_g waveform from the Memory A by pushing *R* and then, using an appropriate button beside the screen, set *Ref A* to *On*; as a result, the waveform observed previously should become duplicated in a different colour (this may be verified by slightly moving the waveform of channel 1 with the *Vertical Position* knob).
2. Set up output voltage measurement as the difference of output terminal voltages:
 - (a) [TBS1052B, TBS1072B] with the *Vertical Scale* knob, change the channel 1 gain to 5 V/div, then hide the channel 1 waveform with the *1* button;
 - (b) [TBS2104] with the buttons *1* and *2*, display channel 1 and 2 waveforms;
 - (c) with the *M* button, show the mathematical operation waveform and ensure that settings displayed in the right-hand side of the screen indicate that this waveform corresponds to the difference of channel 1 and 2 waveforms (*Ch1 – Ch2*);
 - (d) if necessary, set the scale of the mathematical operation waveform to 5 V/div by selecting *Vertical Scale* with an appropriate button beside the screen and set the value with the *Multipurpose* knob.
3. Attach the grounds of both voltage probes from channels 1 and 2 to the point P₁ (if this has not been already done). With the needle tips (after caps are taken off) of the channel 1 and 2 voltage probes, touch the terminals 1 and 2, respectively, of the terminal block J₂.
 In the screen, as the mathematical operation waveform M, the waveform of the converter's output voltage u_o should be displayed. Make sure that the sign of this voltage as measured conforms to the operating principle of the circuit under investigation.
4. Without modifying any settings in the circuit or on the oscilloscope, record the oscilloscope image of the waveforms u_g and u_o in a graphical form
 - in the OpenChoice Desktop application, go to the *Screen Capture* tab;
 - download the screen image to the computer by clicking *Get Screen*;
 - save the oscilloscope image in a graphical form by clicking *Save As*.
5. Disconnect channel 1 and 2 probes from the circuit.
6. Save the resulting ultimate oscilloscope settings for voltage measurements, to a file:
 - go to the *Get & Send Settings* tab;
 - click *Get Settings*;
 - click *Save As* and save the file in your team account.

Current measurement with inductor and output capacitor absent

7. [TBS1052B, TBS1072B] Modify the measurement set-up to enable currents to be measured:
 - (a) upload settings appropriate for current measurements to the oscilloscope:
 - click *Open* and read the file *ustawienia_3u_TBS1052B_il.set*,

- click *Send Settings*;
- (b) detach the voltage probe from channel 1 (without disconnecting it from the circuit);
 - (c) attach the current probe to channel 1 and configure this probe according to the instruction manual available at the laboratory stand.
8. [TBS2104] Set up current measurement:
- (a) attach the output of the current probe amplifier to channel 4 of the oscilloscope;
 - (b) switch the current probe amplifier on and set it up according to the instruction manual available at the laboratory stand, selecting a current-to-voltage conversion ratio appropriate for a current value equal to the output current assumed in design;
 - (c) on the oscilloscope, with buttons *1*, *2*, *M* and *4*, hide channel 1 and 2 waveforms as well as the mathematical operation waveform, and show the channel 4 waveform.
9. Clamp the probe on the wire conducting the current of the inductor (presently shorted) i_L (wire W_3) so that the positive current direction as indicated by an arrow on the probe body is in accordance with the arrow in Fig. 1. A waveform of the current i_L should be displayed on the oscilloscope. Make sure that the sign of the current as measured is positive, which indicates that the probe has been oriented correctly.
10. Supposing that the transistor is an ideal switch, estimate its expected on-state current, considering that the inductor L_1 and the capacitor C_5 are absent from the circuit (i.e., shorted or opened, respectively).
- Check whether the value indicated on the oscilloscope, according to the scale of the respective channel, conforms to this expectation. Otherwise, determine and eliminate the source of such a discrepancy (e.g. incorrectly calculated or applied load resistance, incorrect input or output voltage, incorrect current probe or oscilloscope settings).
11. Without modifying any settings in the circuit or on the oscilloscope, record an oscilloscope image of the u_g and i_L waveforms in a graphical form:
- in the OpenChoice Desktop application, go to the *Screen Capture* tab;
 - download the screen image to the computer by clicking *Get Screen*;
 - save the oscilloscope image in a graphical form by clicking *Save As*.
12. Save the resulting ultimate oscilloscope settings for current measurements, to a file:
- go to the *Get & Send Settings* tab;
 - click *Get Settings*;
 - click *Save As* and save the file in your team account.

Effect of passive components on circuit operation

13. Insert the inductor into the converter circuit:
- (a) bring the input voltage down to zero;
 - (b) unclamp the current probe from the wire;
 - (c) eliminate the short between the terminals of the inductor L_1 ;
 - (d) restore the nominal value of the input voltage U_i , watching that the expected input current still is not significantly exceeded;
 - (e) clamp the current probe back so that to measure the current i_L (wire W_3) considering its direction;
 - (f) verify that the direction (sign) of the current is correct as indicated on the oscilloscope.
14. Without modifying any settings in the circuit or on the oscilloscope, record an oscilloscope image of the u_g and i_L waveforms in a graphical form.
15. [TBS1052B, TBS1072B] Detach the current probe from channel 1 of the oscilloscope (without switching this probe off); and in its place, attach the voltage probe back.

16. Measure the output voltage:
 - (a) through the *Get & Send Settings* tab, from the file saved in step 6, read and upload the voltage measurement settings;
 - (b) with needle tips of the channel 1 and 2 voltage probes, touch the terminals 1 and 2, respectively, of the terminal block J₂;
 - (c) through the *Screen Capture* tab, record an oscilloscope image of the u_g and u_o waveforms in a graphical form.
17. Insert the output capacitor into the converter circuit:
 - (a) bring the input voltage down to zero;
 - (b) unclamp the current probe from the wire;
 - (c) at the appropriate location on the board, solder the capacitor C₅ minding its polarity;
 - (d) using a multimeter set to its circuit continuity test mode, make sure that the “+” terminal of the power supply is connected with the positive terminal of the capacitor C₅;
 - (e) restore the nominal value of the input voltage U_i , watching that the expected input current still is not significantly exceeded;
18. Without modifying any settings in the circuit or on the oscilloscope, record a new oscilloscope image of the u_g and u_o waveforms in a graphical form.
19. Put caps back to the tips of the channel 1 and 2 voltage probes.
20. [TBS1052B, TBS1072B] Detach the voltage probe from channel 1 of the oscilloscope; in its place, attach the current probe back.
21. Measure the inductor current:
 - (a) through the *Get & Send Settings* tab, from the file saved in step 12, read and upload the current measurement settings;
 - (b) clamp the current probe back so that to measure the current i_L (wire W₃) considering its direction
 - (c) verify that the direction (sign) of the current is correct as indicated on the oscilloscope;
 - (d) through the *Screen Capture* tab, record an oscilloscope image of the u_g and i_L waveforms in a graphical form.

Single-pole double-throw semiconductor switch

22. Move the current probe to the wire conducting the diode current i_D , minding its direction according to Fig. 1. Verify that the direction indicated on the oscilloscope is correct.
23. Without modifying any settings in the circuit or on the oscilloscope, record a new oscilloscope image of the u_g and i_D waveforms in a graphical form.
24. Move the current probe to the wire conducting the transistor current i_T , minding its direction according to Fig. 1. Verify that the direction indicated on the oscilloscope is correct.
25. Without modifying any settings in the circuit or on the oscilloscope, record a new oscilloscope image of the u_g and i_T waveforms in a graphical form.

2.4. Buck circuit as a converter of electrical energy

Waveforms under nominal conditions

1. By measuring the input voltage U_i with a multimeter in the terminal block J₁, ensure that its value is equal to the nominal one with an accuracy of ± 0.1 V.
2. Using the potentiometer R₂, modify the duty cycle so that to obtain the nominal value of the output voltage U_o as assumed in design with an accuracy of ± 0.1 V, by measuring this voltage with a multimeter in the terminal block J₂.
3. Move the current probe to the wire conducting the inductor current i_L , minding its direction according to Fig. 1. Verify that the direction indicated on the oscilloscope is correct.
4. Without modifying any settings in the circuit or on the oscilloscope, record a new oscilloscope image of the u_g and i_L waveforms in a graphical form.
5. [TBS1052B, TBS1072B] Detach the current probe from channel 1 of the oscilloscope (without switching this probe off); in its place, attach the voltage probe back.
6. Measure the output voltage:
 - (a) through the *Get & Send Settings* tab, from the file saved in step 6, read and upload the voltage measurement settings;
 - (b) with needle tips of the channel 1 and 2 voltage probes, touch the terminals 1 and 2, respectively, of the terminal block J₂;
 - (c) through the *Screen Capture* tab, record an oscilloscope image of the u_g and u_o waveforms in a graphical form.

Reconfiguring the measurement set-up

A block diagram of the measurement set-up is presented in Fig. 3. Connections to be made or modified, in the way described below, are marked in black, while grey lines show existing connections to be kept unchanged.

7. [TBS1052B, TBS1072B] Detach the voltage probe from channel 1 of the oscilloscope; in its place, attach the current probe back.
8. Set up transistor current measurement:
 - (a) move the current probe to the wire conducting the transistor current i_T , minding its direction according to Fig. 1; verify that the direction indicated on the oscilloscope is correct;
 - (b) through the *Get & Send Settings* tab, from the file saved in step 12, read and upload the current measurement settings;
 - (c) [TBS2104] activate the measurement of the duty cycle of the current:
 - push *Measure*;
 - with an appropriate button beside the screen, select *Ch3*, then with the *Multipurpose* knob, de-select the item *+Duty*;
 - with a button beside the screen, select *Ch4*, then with the *Multipurpose* knob, select the item *+Duty*;
 - close the menu with the *Menu On/Off* button.
9. Bring the input voltage down to zero.
10. Adapt the set-up for measuring the input and output currents:
 - (a) in series with the input, i.e. between the power supply and the terminal block J₁, and in series with the output, i.e. between the terminal block J₂ and the load, insert two multimeters of the same model in a way enabling currents to be measured up to the value expected for the output current, i.e. ensuring that appropriate sockets are used;

- (b) set the multimeters to the DC current measurement mode, considering the expected value as above.

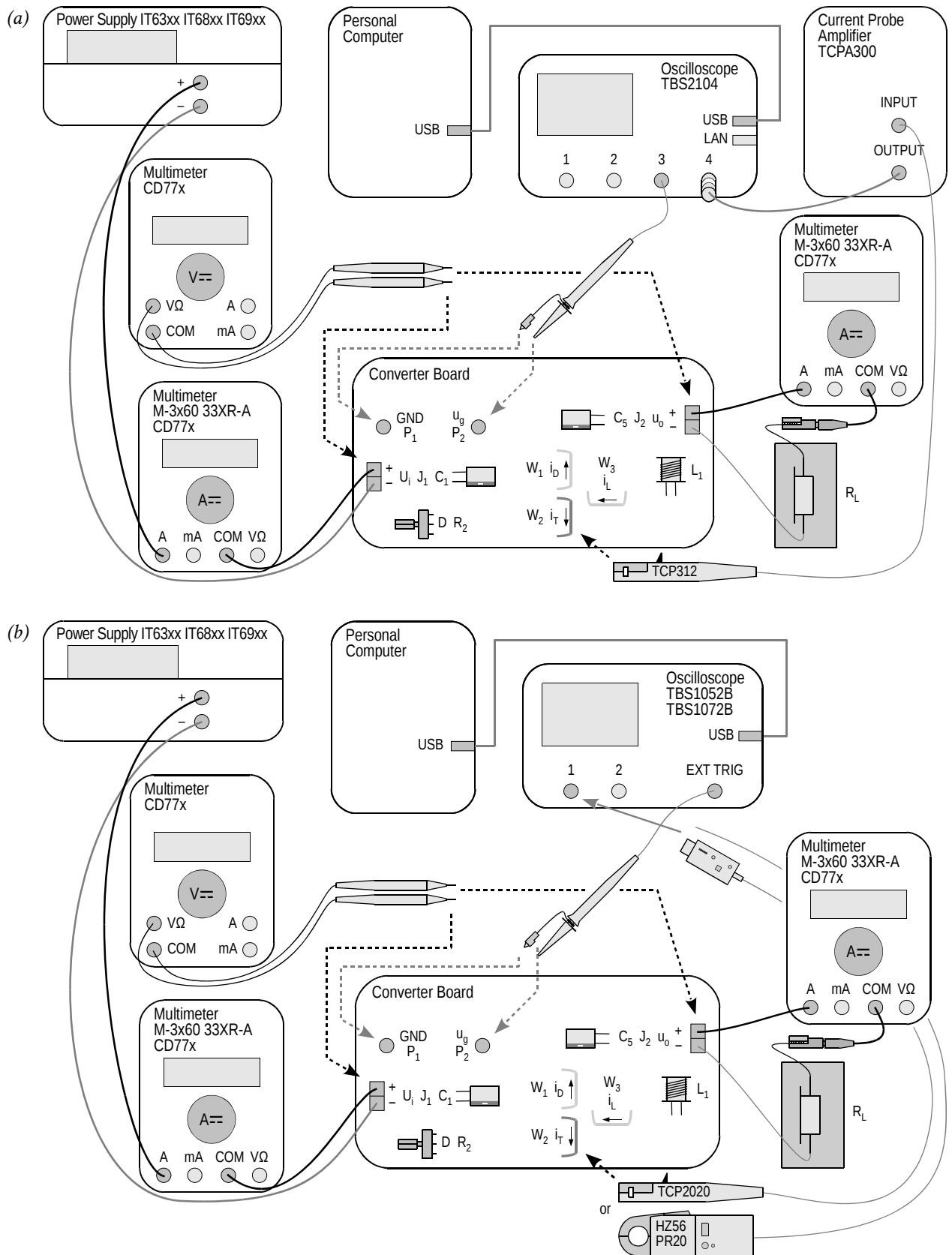


Fig. 3. Block diagram of the measurement set-up for measuring static characteristics: (a) with a TBS2104 oscilloscope; (b) with a TBS1052B or TBS1072B oscilloscope

Measuring static characteristics

Before continuing, the wiring of the multimeters must be verified by the teacher.

11. Restore the nominal input voltage.

During the execution of the following step, exceeding the value of 18 V during adjustment, even momentarily, may cause the integrated circuit U_1 to be damaged!

If a discharged battery indicator (battery symbol) shows up on the multimeter's display, do not go on with measurements, but inform the teacher in order to replace the battery. Otherwise multimeter indications may become erroneous.

12. For 5 to 10 measurement points defined by the value of the input voltage varied within the range determined in design, from the maximum towards the minimum (not in the opposite direction), among which values the nominal value assumed in design must appear:

- (a) on the power supply, set the selected input voltage;
- (b) with the potentiometer R_2 , set the duty cycle so that to obtain the nominal value of the output voltage U_o , by measuring the DC value of this voltage in the terminal block J_2 using a third multimeter;
- (c) from the oscilloscope, read out and write down the duty cycle of the transistor current D_{π} (*Pos Duty* or *Pos. Duty Cycle* indication);
- (d) from the multimeters, read out and write down DC values of the input current I_i and of the output current I_o ;
- (e) using the third multimeter, measure and write down the DC value of the input voltage U_i (at the terminal block J_i) and of the output voltage U_o (in the terminal block J_2).

2.5. Terminating measurements

1. Using the potentiometer R_2 , decrease the duty cycle to its minimum.
2. Bring the power supply voltage down to zero and de-activate its output with the *On/Off* button.
3. Switch the power supply off.
4. Detach the current probe from the circuit.
5. Switch the current probe off in a way appropriate for the model used.
6. [TBS2104] Do not disconnect the current probe from its amplifier or the probe amplifier from the oscilloscope.
[TBS1052B, TBS1072B] Disconnect the current probe from the oscilloscope.
7. Disconnect voltage probes from the circuit. Do not disconnect them, however, from the oscilloscope.
8. Disconnect the circuit from the power supply.
9. Disconnect the load from the circuit.

3. Processing and Analysing Results

3.1. Buck converter topology

Semiconductor switch

1. In Part 1 of the report, include oscilloscope images enabling waveforms of component currents and of the control voltage to be compared against each other: $\{u_g, i_L\}$, $\{u_g, i_D\}$ and $\{u_g, i_T\}$ as recorded in steps 2.3/21, 23 and 25, respectively.
2. Complete Part 1 of the report.

Circuit component roles

3. In Part 2 of the report, set together oscilloscope images recorded in Section 2.3: with the output passive components effectively eliminated (steps 4 and 11), after the short between the inductor's terminals was eliminated (steps 14 and 16) and after the output capacitor was soldered in (steps 18 and 21).
4. Fill in Part 2 of the report.

Operating parameters under nominal conditions

5. Fill in Part 3 of the report.

3.2. Circuit characteristics and effect of transistor

Efficiency

1. Based on your results of measurements performed in step 2.4/12, calculate for each measurement point (see Manual 7K, Sub-chapter 5.5):
 - (a) average input power P_i , from appropriate voltage and current measured (assuming that the input voltage is constant in time);
 - (b) average output power P_o , from appropriate voltage and current measured (assuming that the output voltage is constant in time);
 - (c) efficiency η , from its definition;
 - (d) voltage conversion ratio K_U , from its definition;
 - (e) * current conversion ratio K_I , defined as

$$K_I = \frac{I}{I_{g(0)}} \quad (3.1)$$

2. For each value of the duty cycle D_{IT} , calculate:
 - (a) voltage conversion ratio of an ideal (lossless) converter $K_{U(id)}$, from the analytical formula (see Manual 7K, Sub-chapter 5.2);
 - (b) the ratio of $K_U / K_{U(id)}$, based on your results from sub-steps (a) and 1(d).
3. Collect measurement and calculation results in appropriate tables in Part 4 of the report.
4. Complete Part 4 of the report.

Voltage conversion ratio

5. For a dense set of values of the duty cycle D_{IT} covering their entire possible range, i.e. [0; 1], so that it is later possible to plot a characteristic in the entire range of 0 to 1, making the impression of a smooth line, calculate again the voltage conversion ratio of an ideal converter $K_{U(id)}$ [see step 2(a)]. Put the values obtained in the appropriate table in Part 5 of the report.
6. Complete Part 5 of the report.

Input current

7. * For a dense set of values of the duty cycle D_{IT} covering their entire possible range, i.e. [0; 1], so that it is later possible to plot a characteristic in the entire range of 0 to 1, making the impression of a smooth line, calculate theoretical values of the current conversion ratio K_I by expressing the direct component of the input current $I_{g(0)}$ in the definition (3.1) as a function of the output current using the analytical formula (see 7K, Sub-chapter 5.5). Put the values obtained in the appropriate table in Part 6 of the report.
8. Fill in Part 6 of the report.

Transistor power loss minimisation

9. Fill in Part 7 of the report.

4. Required Knowledge

4.1. Prerequisites

- Buck converter operation (circuit without passive component, with the inductor, and with the output capacitor): electrical schematic, voltage and current waveforms and values with special emphasis on output voltage and input current (Manual 7K, Refs. B and C, Sections 5.2, 5.4 and 5.5)

4.2. Test scope

The problem scope related to this exercise is common with Exercise 7K; it has been given in Manual 7K.

5. References

- [1] Benda V., Gowar J., Grant D. A.: *Power Semiconductor Devices: Theory and Applications*. Wiley, 1999. ISBN 0-471-97644-X.
- [3] Erickson R. W., Maksimović D.: *Fundamentals of Power Electronics. Second Edition*. Springer, 2001. ISBN 0-792-37270-0.



POWER DEVICES AND SYSTEMS LABORATORY

Exercise 3U

Buck DC converter

Exercise and manual elaborated by
Łukasz Starzak

Łódź 2020

Contents

B Exercise Introduction	5
1. Exercise Aim and Plan.....	5
C Experiment.....	7
2. Measurements	7
2.1. Measurement set-up	7
2.2. Preparation for measurements.....	9
Configuring the measurement set-up	9
Supplying the unloaded circuit	9
Configuring the oscilloscope and generator	11
Supplying the loaded circuit	11
2.3. Converter component roles	13
Output voltage measurement without inductor and capacitor	13
Current measurement without inductor and capacitor.....	13
Effect of passive components on circuit operation.....	14
Single-pole double-throw semiconductor switch	15
2.4. Buck circuit as a converter of electrical energy.....	16
Waveforms under nominal conditions	16
Reconfiguring the measurement set-up.....	16
Measuring static characteristics.....	18
2.5. Terminating measurements.....	19
D Results	21
3. Processing and Analysing Results.....	21
3.1. Buck converter topology	21
Semiconductor switch	21
Circuit component roles	21
Operating parameters under nominal conditions.....	21
3.2. Circuit characteristics and effect of transistor	22
Efficiency	22
Voltage conversion ratio.....	22
Input current.....	22
Transistor power loss minimisation	22
E Information	23
4. Required Knowledge.....	23
4.1. Prerequisites	23
4.2. Test scope.....	23
5. References	23

Exercise Introduction

1. Exercise Aim and Plan

The aim of this exercise is to get acquainted with the operation of one of the most common power electronic converters: the DC converter, which at the same time is a typical application of the power MOSFET. In this specific case, the non-isolated (transformerless) step-down (buck) circuit will be investigated, which has the simplest topology and operating principle among DC converters. As in any DC converter, the transistor is there a component of a single-pole double-throw (SPDT) semiconductor switch whose role is to switch over a current from one branch to another one. Based on this example, the pulse width modulation (PWM) method of controlling power semiconductor devices will be illustrated.

This exercise demonstrates that the switched-mode technique using power transistors enables to accomplish useful functions in DC circuits while achieving high energy conversion efficiency. However, obtaining a functional circuit is impossible without using passive power components, whose role will also be experimentally investigated.

The DC converter designed and assembled in the frame of Exercise 7K will be the specific object of investigation. It is also in the manual for Exercise 7K that theoretical material necessary for carrying out this exercise has been provided or referenced.

From among the **components of the power loop**, it will be the semiconductor switch, i.e. the transistor T and the diode D, as well as the output capacitor C_1 that will operate constantly. The inductor L_1 will initially be shorted whereas the output capacitor C_5 will be disconnected from the circuit (unmounted component or one terminal desoldered). These components will be restored to the circuit over the course of the exercise.

The **pulse wave** controlling the transistor u_g comes from an embedded generator. The potentiometer R_2 enables the duty cycle of this waveform to be set.

The measurement point P_1 , connected to the circuit's **ground**, will be used to attach voltage probe grounds. The measurement point P_2 enables the generator **voltage** to be measured. Other voltages will be measured at the J_1 and J_2 terminal blocks.

Observing **current** waveforms is possible by clamping a current probe around one of the wires led out of the board: W_1 for the diode current i_D , W_2 for the transistor current i_T or W_3 for the inductor current i_L .

Depending on the stand, a four-channel or a two-channel **oscilloscope** may be used. In the latter case, due to the limited number of channels, it will be necessary to switch over voltage and current probes, additionally using the external trigger input. Measurement procedures are described further in this manual, along with oscilloscope model designations when procedures differ.

2.2. Preparation for measurements

Configuring the measurement set-up

A simplified block diagram of the measurement set-up, including the two possible oscilloscope models is presented in Fig. 2. It should be assembled and configured in the way described below and in the specified sequence. If an oscilloscope model designation is given in a given step, then this step concerns this specific model, while it should not be carried out in case another model is used.

In order not to waste time, you should continue with following steps in parallel with step 1.

1. Switch the computer on. After logon completes, switch the oscilloscope on and, if necessary, set up its connection to the computer following a manual available at the laboratory stand.
2. In the converter board, keep the output capacitor C_5 disconnected and the inductor L_1 shorted. Keep the terminals of the block J_2 unoccupied.
3. Switch the power supply on without activating its output.
4. Connect the power supply's output with the converter's input (U_i voltage), i.e. with the terminal block J_1 , minding the polarity of the capacitor C_1 .
5. Using a multimeter set to its circuit continuity test mode, verify that the „+” terminal of the power supply is connected to the VCC pin (pin 8) of the integrated circuit U_1 and that its „-” terminal is connected to the GND pin (pin 1).
6. Attach the voltage probe or probes with a 1:10 attenuation, connected to the input or inputs of the oscilloscope, so as to measure the generator's output voltage u_g (measurement points P_1 and P_2), considering its direction according to Fig. 1:
 - [TBS2104] in channel 3;
 - [TBS1052B, TBS1072B] in the external trigger channel (*Ext Trig*) and in channel 1.

Voltage probe grounds (alligator clip connectors) are shorted together inside the oscilloscope and connected to the supply network protective earth. They must be therefore always connected to the same electric potential. Any other connection might result in current flowing through the oscilloscope, which would damage its input circuitry!

Supplying the unloaded circuit

7. Within your results of Exercise 7K (Task 7), check out the expected input current of an unloaded converter (or calculate it again as the sum of the maximum supply current of the integrated circuit U_1 according to its documentation and the maximum current of the generator's RC network as assumed in design.

While executing the following step, pay attention not to exceed the value of 18 V at any moment, as this might damage the integrated circuit U_1 .

8. Supply the unloaded converter:
 - (a) if a multi-channel power supply is used, select the channel used with the *Local/CH* button;
 - (b) push *I-Set* and set the current limit to 100 mA;
 - (c) push *V-Set* and set the voltage to 0 V;
 - (d) activate the output with the *On/Off* button and display embedded meter indications with the *Meter* button;

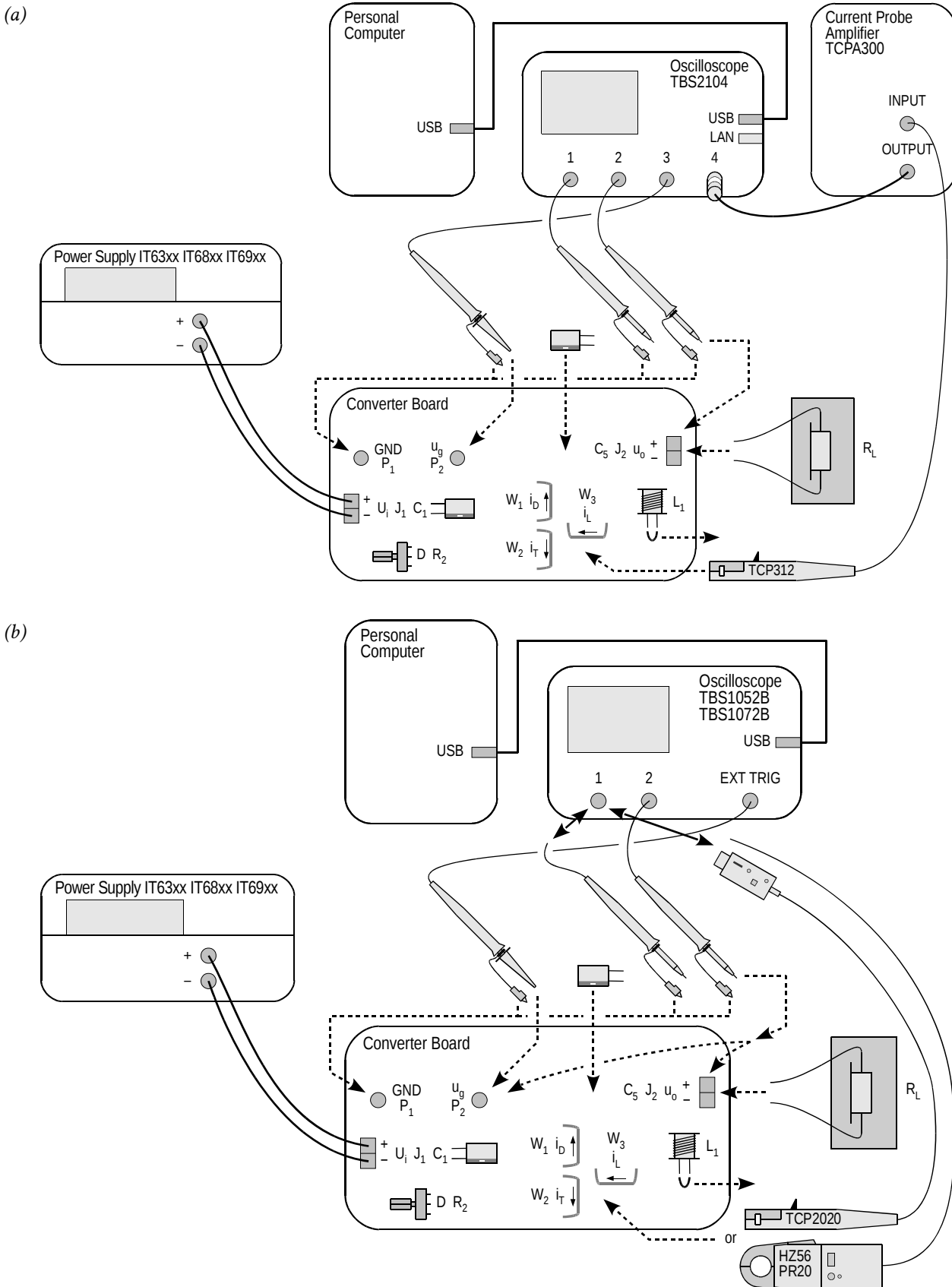


Fig. 2. Block diagram of the measurement set-up for recording time waveforms: (a) with a TBS2104 oscilloscope; (b) with a TBS1052B or TBS1072B oscilloscope

Read the contents of the following step in their entirety first and only then proceed with its execution.

- (e) using the knob, gradually increase the supply voltage to the nominal value of the input voltage U_i , watching that the current indicated by the power supply's ammeter does not significantly (by more than 50%) exceed the expected value as established in step 7; otherwise, deactivate the power supply's output with the *On/Off* button and verify your connections again.

Configuring the oscilloscope and generator

9. Using the oscilloscope communication software, upload initial settings to the oscilloscope:
- go to the *Get & Send Settings* tab;
 - click *Open* and read the file *ustawienia_3u_tbs2104 Ug_uo_il.set* or *ustawienia_3u_TBS1052B_Ug_uo.set*, as appropriate;
 - click *Send Settings*.

In the oscilloscope's screen, a stable, continuously refreshed pulse wave should be displayed, as attested, among others, by the message "Trig'd" (*Triggered*) appearing above the graticule. If this does not happen, ask the teacher to check oscilloscope settings.

10. In case of need, adjust:
- the time base and the trigger event position (*Horizontal Scale* and *Horizontal Position* knobs) so that 3 to 7 periods of the u_g voltage are visible; the trigger instant, indicated by an arrow at the top of the graticule, must appear within the screen, i.e. it cannot be located at either end of the graticule;
 - gain and zero level position (*Vertical Scale* and *Position* knobs) of the channel where the generator voltage is measured so that its waveform is easily observed, is located at the very bottom of the screen and extends vertically over approximately one division.
11. Using the potentiometer R_2 , using the *Pos Duty* or *Pos. Duty Cycle* measurement result displayed on the oscilloscope, coarsely set half of the expected nominal (i.e. one corresponding to the nominal input voltage U_i) duty cycle as calculated in Exercise 7K (Task 4).

Setting a duty cycle higher than the one indicated above at this moment may cause the transistor or the diode to be destroyed as a result of excessive power dissipation in the circuit where output passive components are absent. It will be only possible to increase the duty cycle at a specified moment after passive components are connected.

12. Bring the supply voltage down to zero.

Suppling the loaded circuit

13. To the converter's output (terminal block J_2), attach a load in the form of a resistor, or a set of resistors, having a resistance such that at the nominal output voltage U_o as assumed in design, the assumed nominal output current I_o is obtained, and having a resultant admissible power of at least twice the nominal output power of the converter.
14. Place the load on a heat resistant pad. Ensure that no component or wire touches the load; this equally applies to voltage and current probe cables. Otherwise, wire or termination insulation can melt.

The above conditions must be kept ensured over the entire course of this exercise!

Do not touch the load while realising this exercise, as, depending on operating conditions, its temperature can rise above 100 °C. Risk of burn!

15. Calculate the expected input current of the loaded converter for the duty cycle D set above, the nominal input voltage U_i and the resistance of the load used R_L (see Exercise 7K, Task 8).
16. On the power supply, push *I-Set* and set current limit to 3 A.

17. Push *V-Set* and gradually restore the nominal input voltage U_i , watching that the current does not significantly (by more than 20%) exceed the expected value as established in step 15; otherwise, de-activate the power supply's output with the *On/Off* button and verify the circuit again.

From this moment on, all until the completion of the exercise, under no circumstances should a different time base (*Horizontal Scale* knob) or trigger instant position (*Horizontal Position* knob) be set! This would cause de-synchronisation between consecutive oscilloscope images, thus rendering their analysis impossible at the result processing stage.

From this moment on, the duty cycle of the generator voltage (thus the setting of the potentiometer R_2) should not be changed unless you are explicitly told to! This would cause an inconsistency between consecutive oscilloscope images, thus rendering their analysis impossible at the result processing stage.

2.3. Converter component roles

Output voltage measurement with inductor and output capacitor absent

1. [TBS1052B, TBS1072B] Na oscyloskopie zachowaj obraz napięcia u_g :
 - (a) save the control voltage waveform u_g in the oscilloscope's memory:
 - push *Save Recall*,
 - using the appropriate button beside the screen, set *Action* to *Save Waveform*,
 - select saving to oscilloscope memory, *Save To: Ref*,
 - set *Source* to channel 1 (*CH1*),
 - select destination as Memory A, *To: Ref A*,
 - push *Save*;
 - (b) display the u_g waveform from the Memory A by pushing *R* and then, using an appropriate button beside the screen, set *Ref A* to *On*; as a result, the waveform observed previously should become duplicated in a different colour (this may be verified by slightly moving the waveform of channel 1 with the *Vertical Position* knob).
2. Set up output voltage measurement as the difference of output terminal voltages:
 - (a) [TBS1052B, TBS1072B] with the *Vertical Scale* knob, change the channel 1 gain to 5 V/div, then hide the channel 1 waveform with the *1* button;
 - (b) [TBS2104] with the buttons *1* and *2*, display channel 1 and 2 waveforms;
 - (c) with the *M* button, show the mathematical operation waveform and ensure that settings displayed in the right-hand side of the screen indicate that this waveform corresponds to the difference of channel 1 and 2 waveforms (*Ch1 – Ch2*);
 - (d) if necessary, set the scale of the mathematical operation waveform to 5 V/div by selecting *Vertical Scale* with an appropriate button beside the screen and set the value with the *Multipurpose* knob.
3. Attach the grounds of both voltage probes from channels 1 and 2 to the point P₁ (if this has not been already done). With the needle tips (after caps are taken off) of the channel 1 and 2 voltage probes, touch the terminals 1 and 2, respectively, of the terminal block J₂.
 In the screen, as the mathematical operation waveform M, the waveform of the converter's output voltage u_o should be displayed. Make sure that the sign of this voltage as measured conforms to the operating principle of the circuit under investigation.
4. Without modifying any settings in the circuit or on the oscilloscope, record the oscilloscope image of the waveforms u_g and u_o in a graphical form
 - in the OpenChoice Desktop application, go to the *Screen Capture* tab;
 - download the screen image to the computer by clicking *Get Screen*;
 - save the oscilloscope image in a graphical form by clicking *Save As*.
5. Disconnect channel 1 and 2 probes from the circuit.
6. Save the resulting ultimate oscilloscope settings for voltage measurements, to a file:
 - go to the *Get & Send Settings* tab;
 - click *Get Settings*;
 - click *Save As* and save the file in your team account.

Current measurement with inductor and output capacitor absent

7. [TBS1052B, TBS1072B] Modify the measurement set-up to enable currents to be measured:
 - (a) upload settings appropriate for current measurements to the oscilloscope:
 - click *Open* and read the file *ustawienia_3u_TBS1052B_il.set*,

- click *Send Settings*;
- (b) detach the voltage probe from channel 1 (without disconnecting it from the circuit);
 - (c) attach the current probe to channel 1 and configure this probe according to the instruction manual available at the laboratory stand.
8. [TBS2104] Set up current measurement:
- (a) attach the output of the current probe amplifier to channel 4 of the oscilloscope;
 - (b) switch the current probe amplifier on and set it up according to the instruction manual available at the laboratory stand, selecting a current-to-voltage conversion ratio appropriate for a current value equal to the output current assumed in design;
 - (c) on the oscilloscope, with buttons *1*, *2*, *M* and *4*, hide channel 1 and 2 waveforms as well as the mathematical operation waveform, and show the channel 4 waveform.
9. Clamp the probe on the wire conducting the current of the inductor (presently shorted) i_L (wire W_3) so that the positive current direction as indicated by an arrow on the probe body is in accordance with the arrow in Fig. 1. A waveform of the current i_L should be displayed on the oscilloscope. Make sure that the sign of the current as measured is positive, which indicates that the probe has been oriented correctly.
10. Supposing that the transistor is an ideal switch, estimate its expected on-state current, considering that the inductor L_1 and the capacitor C_5 are absent from the circuit (i.e., shorted or opened, respectively).
- Check whether the value indicated on the oscilloscope, according to the scale of the respective channel, conforms to this expectation. Otherwise, determine and eliminate the source of such a discrepancy (e.g. incorrectly calculated or applied load resistance, incorrect input or output voltage, incorrect current probe or oscilloscope settings).
11. Without modifying any settings in the circuit or on the oscilloscope, record an oscilloscope image of the u_g and i_L waveforms in a graphical form:
- in the OpenChoice Desktop application, go to the *Screen Capture* tab;
 - download the screen image to the computer by clicking *Get Screen*;
 - save the oscilloscope image in a graphical form by clicking *Save As*.
12. Save the resulting ultimate oscilloscope settings for current measurements, to a file:
- go to the *Get & Send Settings* tab;
 - click *Get Settings*;
 - click *Save As* and save the file in your team account.

Effect of passive components on circuit operation

13. Insert the inductor into the converter circuit:
- (a) bring the input voltage down to zero;
 - (b) unclamp the current probe from the wire;
 - (c) eliminate the short between the terminals of the inductor L_1 ;
 - (d) restore the nominal value of the input voltage U_i , watching that the expected input current still is not significantly exceeded;
 - (e) clamp the current probe back so that to measure the current i_L (wire W_3) considering its direction;
 - (f) verify that the direction (sign) of the current is correct as indicated on the oscilloscope.
14. Without modifying any settings in the circuit or on the oscilloscope, record an oscilloscope image of the u_g and i_L waveforms in a graphical form.
15. [TBS1052B, TBS1072B] Detach the current probe from channel 1 of the oscilloscope (without switching this probe off); and in its place, attach the voltage probe back.

16. Measure the output voltage:
 - (a) through the *Get & Send Settings* tab, from the file saved in step 6, read and upload the voltage measurement settings;
 - (b) with needle tips of the channel 1 and 2 voltage probes, touch the terminals 1 and 2, respectively, of the terminal block J₂;
 - (c) through the *Screen Capture* tab, record an oscilloscope image of the u_g and u_o waveforms in a graphical form.
17. Insert the output capacitor into the converter circuit:
 - (a) bring the input voltage down to zero;
 - (b) unclamp the current probe from the wire;
 - (c) at the appropriate location on the board, solder the capacitor C₅ minding its polarity;
 - (d) using a multimeter set to its circuit continuity test mode, make sure that the “+” terminal of the power supply is connected with the positive terminal of the capacitor C₅;
 - (e) restore the nominal value of the input voltage U_i , watching that the expected input current still is not significantly exceeded;
18. Without modifying any settings in the circuit or on the oscilloscope, record a new oscilloscope image of the u_g and u_o waveforms in a graphical form.
19. Put caps back to the tips of the channel 1 and 2 voltage probes.
20. [TBS1052B, TBS1072B] Detach the voltage probe from channel 1 of the oscilloscope; in its place, attach the current probe back.
21. Measure the inductor current:
 - (a) through the *Get & Send Settings* tab, from the file saved in step 12, read and upload the current measurement settings;
 - (b) clamp the current probe back so that to measure the current i_L (wire W₃) considering its direction
 - (c) verify that the direction (sign) of the current is correct as indicated on the oscilloscope;
 - (d) through the *Screen Capture* tab, record an oscilloscope image of the u_g and i_L waveforms in a graphical form.

Single-pole double-throw semiconductor switch

22. Move the current probe to the wire conducting the diode current i_D , minding its direction according to Fig. 1. Verify that the direction indicated on the oscilloscope is correct.
23. Without modifying any settings in the circuit or on the oscilloscope, record a new oscilloscope image of the u_g and i_D waveforms in a graphical form.
24. Move the current probe to the wire conducting the transistor current i_T , minding its direction according to Fig. 1. Verify that the direction indicated on the oscilloscope is correct.
25. Without modifying any settings in the circuit or on the oscilloscope, record a new oscilloscope image of the u_g and i_T waveforms in a graphical form.

2.4. Buck circuit as a converter of electrical energy

Waveforms under nominal conditions

1. By measuring the input voltage U_i with a multimeter in the terminal block J₁, ensure that its value is equal to the nominal one with an accuracy of ± 0.1 V.
2. Using the potentiometer R₂, modify the duty cycle so that to obtain the nominal value of the output voltage U_o as assumed in design with an accuracy of ± 0.1 V, by measuring this voltage with a multimeter in the terminal block J₂.
3. Move the current probe to the wire conducting the inductor current i_L , minding its direction according to Fig. 1. Verify that the direction indicated on the oscilloscope is correct.
4. Without modifying any settings in the circuit or on the oscilloscope, record a new oscilloscope image of the u_g and i_L waveforms in a graphical form.
5. [TBS1052B, TBS1072B] Detach the current probe from channel 1 of the oscilloscope (without switching this probe off); in its place, attach the voltage probe back.
6. Measure the output voltage:
 - (a) through the *Get & Send Settings* tab, from the file saved in step 6, read and upload the voltage measurement settings;
 - (b) with needle tips of the channel 1 and 2 voltage probes, touch the terminals 1 and 2, respectively, of the terminal block J₂;
 - (c) through the *Screen Capture* tab, record an oscilloscope image of the u_g and u_o waveforms in a graphical form.

Reconfiguring the measurement set-up

A block diagram of the measurement set-up is presented in Fig. 3. Connections to be made or modified, in the way described below, are marked in black, while grey lines show existing connections to be kept unchanged.

7. [TBS1052B, TBS1072B] Detach the voltage probe from channel 1 of the oscilloscope; in its place, attach the current probe back.
8. Set up transistor current measurement:
 - (a) move the current probe to the wire conducting the transistor current i_T , minding its direction according to Fig. 1; verify that the direction indicated on the oscilloscope is correct;
 - (b) through the *Get & Send Settings* tab, from the file saved in step 12, read and upload the current measurement settings;
 - (c) [TBS2104] activate the measurement of the duty cycle of the current:
 - push *Measure*;
 - with an appropriate button beside the screen, select *Ch3*, then with the *Multipurpose* knob, de-select the item *+Duty*;
 - with a button beside the screen, select *Ch4*, then with the *Multipurpose* knob, select the item *+Duty*;
 - close the menu with the *Menu On/Off* button.
9. Bring the input voltage down to zero.
10. Adapt the set-up for measuring the input and output currents:
 - (a) in series with the input, i.e. between the power supply and the terminal block J₁, and in series with the output, i.e. between the terminal block J₂ and the load, insert two multimeters of the same model in a way enabling currents to be measured up to the value expected for the output current, i.e. ensuring that appropriate sockets are used;

- (b) set the multimeters to the DC current measurement mode, considering the expected value as above.

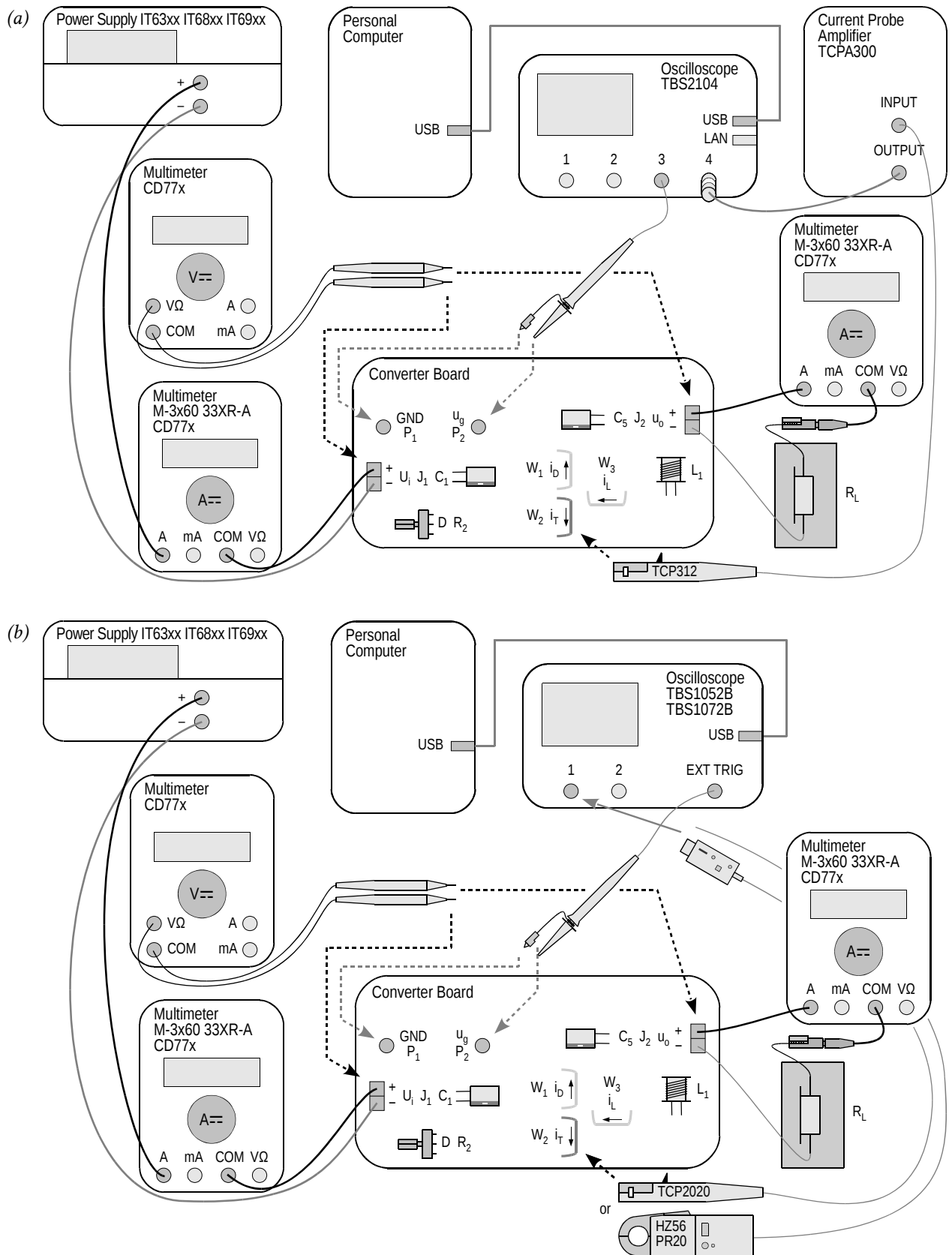


Fig. 3. Block diagram of the measurement set-up for measuring static characteristics: (a) with a TBS2104 oscilloscope; (b) with a TBS1052B or TBS1072B oscilloscope

Measuring static characteristics

Before continuing, the wiring of the multimeters must be verified by the teacher.

11. Restore the nominal input voltage.

During the execution of the following step, exceeding the value of 18 V during adjustment, even momentarily, may cause the integrated circuit U_1 to be damaged!

If a discharged battery indicator (battery symbol) shows up on the multimeter's display, do not go on with measurements, but inform the teacher in order to replace the battery. Otherwise multimeter indications may become erroneous.

12. For 5 to 10 measurement points defined by the value of the input voltage varied within the range determined in design, from the maximum towards the minimum (not in the opposite direction), among which values the nominal value assumed in design must appear:

- (a) on the power supply, set the selected input voltage;
- (b) with the potentiometer R_2 , set the duty cycle so that to obtain the nominal value of the output voltage U_o , by measuring the DC value of this voltage in the terminal block J_2 using a third multimeter;
- (c) from the oscilloscope, read out and write down the duty cycle of the transistor current D_{π} (*Pos Duty* or *Pos. Duty Cycle* indication);
- (d) from the multimeters, read out and write down DC values of the input current I_i and of the output current I_o ;
- (e) using the third multimeter, measure and write down the DC value of the input voltage U_i (at the terminal block J_i) and of the output voltage U_o (in the terminal block J_2).

2.5. Terminating measurements

1. Using the potentiometer R_2 , decrease the duty cycle to its minimum.
2. Bring the power supply voltage down to zero and de-activate its output with the *On/Off* button.
3. Switch the power supply off.
4. Detach the current probe from the circuit.
5. Switch the current probe off in a way appropriate for the model used.
6. [TBS2104] Do not disconnect the current probe from its amplifier or the probe amplifier from the oscilloscope.
[TBS1052B, TBS1072B] Disconnect the current probe from the oscilloscope.
7. Disconnect voltage probes from the circuit. Do not disconnect them, however, from the oscilloscope.
8. Disconnect the circuit from the power supply.
9. Disconnect the load from the circuit.

3. Processing and Analysing Results

3.1. Buck converter topology

Semiconductor switch

1. In Part 1 of the report, include oscilloscope images enabling waveforms of component currents and of the control voltage to be compared against each other: $\{u_g, i_L\}$, $\{u_g, i_D\}$ and $\{u_g, i_T\}$ as recorded in steps 2.3/21, 23 and 25, respectively.
2. Complete Part 1 of the report.

Circuit component roles

3. In Part 2 of the report, set together oscilloscope images recorded in Section 2.3: with the output passive components effectively eliminated (steps 4 and 11), after the short between the inductor's terminals was eliminated (steps 14 and 16) and after the output capacitor was soldered in (steps 18 and 21).
4. Fill in Part 2 of the report.

Operating parameters under nominal conditions

5. Fill in Part 3 of the report.

3.2. Circuit characteristics and effect of transistor

Efficiency

1. Based on your results of measurements performed in step 2.4/12, calculate for each measurement point (see Manual 7K, Sub-chapter 5.5):
 - (a) average input power P_i , from appropriate voltage and current measured (assuming that the input voltage is constant in time);
 - (b) average output power P_o , from appropriate voltage and current measured (assuming that the output voltage is constant in time);
 - (c) efficiency η , from its definition;
 - (d) voltage conversion ratio K_U , from its definition;
 - (e) * current conversion ratio K_I , defined as

$$K_I = \frac{I}{I_{g(0)}} \quad (3.1)$$

2. For each value of the duty cycle D_{IT} , calculate:
 - (a) voltage conversion ratio of an ideal (lossless) converter $K_{U(id)}$, from the analytical formula (see Manual 7K, Sub-chapter 5.2);
 - (b) the ratio of $K_U / K_{U(id)}$, based on your results from sub-steps (a) and 1(d).
3. Collect measurement and calculation results in appropriate tables in Part 4 of the report.
4. Complete Part 4 of the report.

Voltage conversion ratio

5. For a dense set of values of the duty cycle D_{IT} covering their entire possible range, i.e. [0; 1], so that it is later possible to plot a characteristic in the entire range of 0 to 1, making the impression of a smooth line, calculate again the voltage conversion ratio of an ideal converter $K_{U(id)}$ [see step 2(a)]. Put the values obtained in the appropriate table in Part 5 of the report.
6. Complete Part 5 of the report.

Input current

7. * For a dense set of values of the duty cycle D_{IT} covering their entire possible range, i.e. [0; 1], so that it is later possible to plot a characteristic in the entire range of 0 to 1, making the impression of a smooth line, calculate theoretical values of the current conversion ratio K_I by expressing the direct component of the input current $I_{g(0)}$ in the definition (3.1) as a function of the output current using the analytical formula (see 7K, Sub-chapter 5.5). Put the values obtained in the appropriate table in Part 6 of the report.
8. Fill in Part 6 of the report.

Transistor power loss minimisation

9. Fill in Part 7 of the report.

4. Required Knowledge

4.1. Prerequisites

- Buck converter operation (circuit without passive component, with the inductor, and with the output capacitor): electrical schematic, voltage and current waveforms and values with special emphasis on output voltage and input current (Manual 7K, Refs. B and C, Sections 5.2, 5.4 and 5.5)

4.2. Test scope

The problem scope related to this exercise is common with Exercise 7K; it has been given in Manual 7K.

5. References

- [1] Benda V., Gowar J., Grant D. A.: *Power Semiconductor Devices: Theory and Applications*. Wiley, 1999. ISBN 0-471-97644-X.
- [3] Erickson R. W., Maksimović D.: *Fundamentals of Power Electronics. Second Edition*. Springer, 2001. ISBN 0-792-37270-0.