POWER DEVICES AND SYSTEMS LABORATORY

Exercise 5U

Two-Stage Cycloconverter
Bridge Rectifier
Half-Bridge Inverter
BJT Applications

**Caution! Dangerous voltages are present in the measurement set-up.
Danger of shock if safety guidelines given are not followed!**

Exercise and manual elaborated by
Łukasz Starzak

Łódź 2019

Contents

B

Exercise Introduction

1. Exercise Aim and Plan

In this exercise, an electronic ballast for a Compact Fluorescent Lamp (CFL) will be investigated as a typical application example of power Bipolar Junction Transistors. The BJTs applied in this circuit are high-voltage but small-power devices (with a rated power of the order of 0.1 W to 1 W). Measurement results will be used to analyse how a particular transistor has been selected for the investigated circuit.

The application chosen for this demonstration creates an opportunity to get acquainted with a typical structure (as considered at the functional block level) of modern electronic cycloconverters. Instead of complex single-stage structures used in the past, it is a two-stage structure, which is, however, composed of two simple converters: a rectifier and an inverter. The operation of these circuits will be analysed, including their interaction with the supply grid. On this occasion, two of the typical operating configurations of power semiconductor devices will be presented: the bridge and the half-bridge.

2. Fluorescent Lamp Electronic Ballast

2.1. Recommended reading

Ref.	Textbook	Excerpt	Equivalent in the Polish Manual	Complementary Reading	Complements in this Manual
A	Ben	6.6	2.1		
B	[14]	8.1.1 The fluorescent lamp, The ballast, Switchstart ballast operation, *from* Why electronic ballasts? *to* Compact and light weight, Electronic ballast topologies, The half bridge inverter, Voltage fed half bridge inverter	2.2, 2.3.a,c-d, 2.4		
C	[22]	2.1, 2.2, 2.3, 2.4, 2.5, 4.2.1, Appendix 1	2.4.c, 2.5	[18] Controlling the Fluorescent Lamp, Half Bridge Topology Analysis, Half Bridge Design, Breakdown Voltage	

Also read again: Manual 0, Ref. H, 3.1.2.

Ref. A is contained in the document already published as Refs. AB for Manual 5P.

3. Rectifiers

3.1. Recommended reading

Ref.	Textbook	Excerpt	Equivalent in the Polish Manual	Complementary Reading	Complements in this Manual
D	Moh	5-1 5-2-1 5-3, 5-3-1, 5-3-3, 5-3-4, 5-3-4-1, 5-3-4-2, 5-3-4-3, 5-3-4-4	3.1, 3.2, 3.3		
E	Eri	16.3.2, 16.6	3.3.b-c		

C

Experiment

4. Measurements

4.1. Experimental circuit

Ballast under investigation

The appliance under investigation in this exercise is a compact fluorescent lamp, F10DBX/T4/840/4P, whose nominal power is P_n = 11 W, with an electronic ballast whose nominal supply voltage is U_n = 230 V. A complete schematic diagram of the ballast is shown in Fig. 1. As it can be seen (see Ref. B), this circuit belongs to the half-bridge family. In the AC diagonal of the bridge, the lamp E_{fl}, the choke (inductor) L_1 and the transformer's primary winding T_{1A} have been inserted.

The different functional blocks (according to Fig. 4 in Ref. B) comprise:

- a rectifier, which is the diode bridge $D_{R1}...D_{R4}$;
- a low-pass filter, which is the capacitor C_4;
- an inverter, which is the half-bridge composed of Q_1, D_1, Q_2, D_2, C_1, C_2, where Q_1 and Q_2 are high-voltage BJTs, BUT100;
- an actual ballast, which is the inductor L_1;
- an output current shaping circuit, which is the resonant circuit composed of L_1, C_1 and C_2;
- an ignition circuit, which is the resonant circuit composed of L_1 and C_3;
- an initial heating circuit, which is the capacitor C_3;
- an electromagnetic disturbance filter (located after the rectifier in this case), which is the second order circuit composed of the choke L_2 and the capacitors C_1 and C_2.

The operating principle of this circuit has been explained in Ref. C, including the role of the components R_2, C_5, D_3 and D_4 during circuit start-up. The task of the small-value capacitor C_6 is to slow down changes of the half-bridge leg middle point voltage u_{mp} during transistor switching in order to limit the high-frequency disturbances generated.

The inverter is voltage-fed: the rectified voltage u_{rect} from the rectifier's filter output is fed into the inverter's input. The investigated circuit is one of moderate complexity; there are solutions in the market with an even smaller component count.

An electronic ballast is a multi-stage power circuit. Each of its two stages, the rectifier and the inverter, has its own input and output. In order to differentiate between them, we will not apply the subscripts "i" and "o" which are ambiguous in this case. Instead, we will denote:

- the rectifier's input, with "g" for "grid";

- the rectifier's output, which is also the inverter's input, with "rect" for "rectified";

- the inverter's output, i.e. its AC diagonal, with "inv" for "inverter";

- the output of the complete power converter, i.e. the lamp's terminals, with "fl" for "fluorescent lamp."
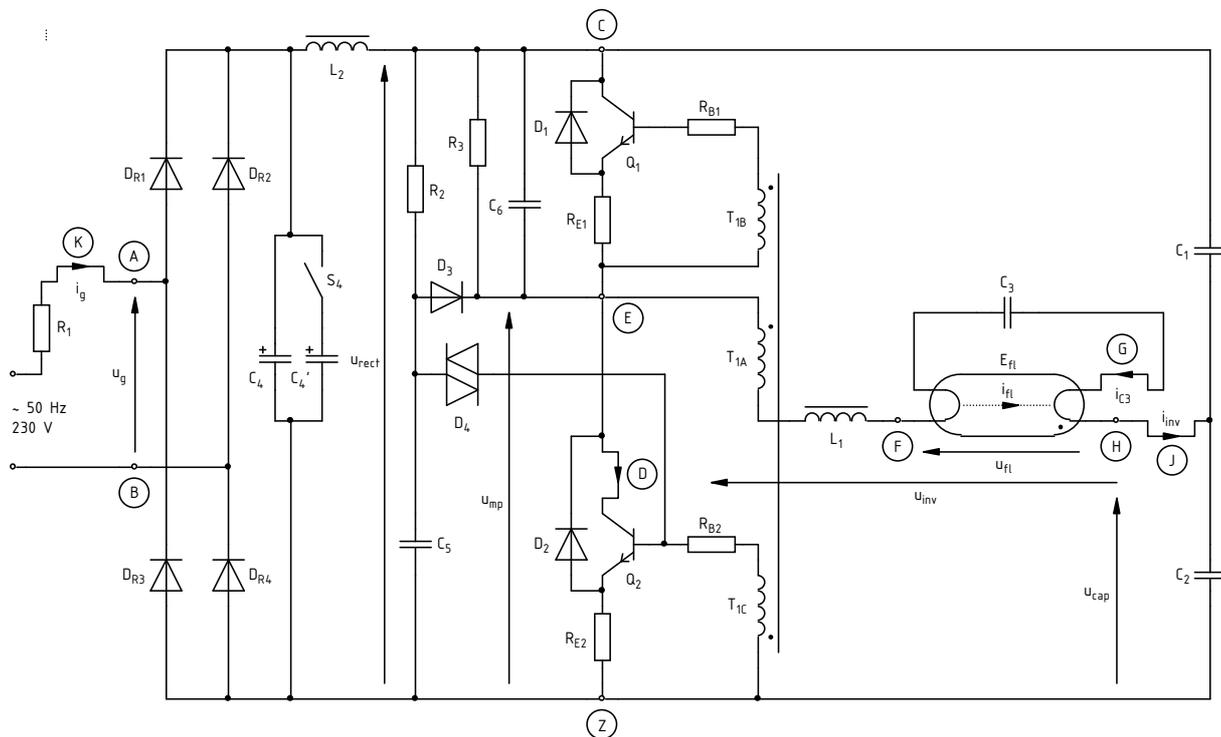
Fig. 1. Electrical schematic of the fluorescent lamp ballast under investigation with measurement points and wires marked that have been lead out to its panel

Conducting measurements

The experimental circuit enables voltage measurements using voltage probes. Banana sockets and connectors are provided for this purpose that enable probes to be attached. Socket locations in the diagrams (Figs. 1 and 2) are marked with empty dots and labelled with letters as A, B, C, E, F, H and Z. The point Z will be considered the circuit's ground. Therefore, the potential at point C is equal to the rectified voltage u_{rect} that supplies the inverter. Most voltages will be measured with respect to point Z.

It is also possible to measure currents by clamping a current probe around one of the wires led out above the circuit's top panel and on its back side. The locations of these wires is marked in the diagrams (Figs. 1 and 2) with offset lines and letters D, G, J and K. Arrows shown both in the diagrams and on the panel indicate current directions to be assumed as positive.

To ease certain measurements and increase user safety, the circuit has an isolation transformer embedded at its input. It can be connected or disconnected from the circuit (which is necessary for

some measurements) using two switches found on the rear side of the circuit's casing. Both these switches should always be set in the same position (either "I" or "II").

Additionally, the circuit makes enables the capacitance C_4 to be changed. This is done using the small switch S4 on the circuit's panel, located between the sockets Z and C (see Fig. 2). Setting this switch to "I" results in an additional capacitor C_4' with a value of 2.2 µF being connected in parallel with the capacitor C_4 whose value is 4.7 µF.

> **Warning! Dangerous voltages are present in the circuit. The following safety rules must therefore be obligatorily observed.**
>
> 1. **Due to their high amplitudes, all voltages with respect to the ground present in the circuit, all voltages should be measured using probes with an attenuation of 1:100 and a maximum admissible peak voltage of at least 600 V.**
>
> 2. **After power supply is switched on, it is forbidden to touch sockets located on the panel or leads protruding from banana connectors inserted there.**
>
> 3. **Measurement connectors with relatively short leads should be used, just as necessary to attach a voltage probe.**
>
> 4. **Inserting, removing or moving banana connectors is only permitted when power supply is switched off.**
>
> **Not respecting the above rules may lead to electric shock with a voltage of above 300 V!**

4.2. Two-stage AC/AC converter

Circuit preparation

A block diagram of the measurement set-up is presented in Fig. 2. Its assembly and configuration is to be carried out <u>in the way described below, following the order of actions specified</u>.

To avoid losing time, proceed with subsequent steps in parallel with step 1.

1. Switch the computer on. <u>After logon completes</u>, switch the oscilloscope on and, <u>if necessary</u>, set up its connection to the computer following a manual available at the laboratory stand.

2. Configure the experimental circuit:

   (a) set the power supply switch S3 on the circuit's panel to "O";

   (b) set <u>both</u> switches found on the back side of the circuit's casing to "II";

   (c) set the capacitor's switch S4 on the circuit's panel to "O".
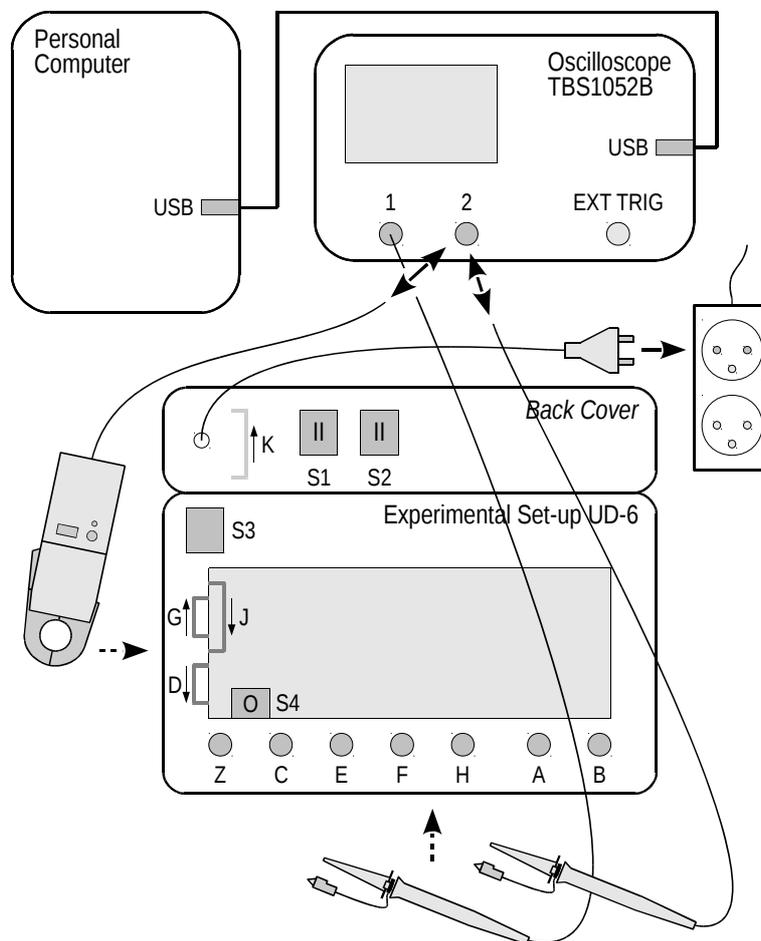
Fig. 2. Block diagram of the measurement set-up for investigating ballast operation with element layout on the experimental circuit's panel

3. Plug the circuit to the mains through the cable and the plug lead out from the back side of the circuit's casing. The lamp should not be lit at this moment.

4. 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_5u_fal_tbs1052.set*;
- click *Send Settings* (<u>not</u> *Send to multiple*);
- make sure that at the bottom of the screen, <u>six results</u> of various measurements are displayed (those for channel 1 will be replaced with "?" signs until this channel is activated later on), otherwise click *Send Settings* again,
- return to the *Screen Capture* tab.

Converter input-side voltages

5. Display and record the grid voltage:

   (a) plug two measurement connectors in the sockets A and B; remove any connectors from the remaining sockets;

   (b) connect voltage probes <u>with an attenuation of 1:100</u> to both channel inputs of the oscilloscope;

   (c) connect the <u>channel 2</u> probe to the circuit so as to measure the grid voltage u_g; Any other probes should remain disconnected from the circuit.

   Before proceeding with the next sub-step, connections in the measurement set-up must be checked by the teacher!

   (d) switch the circuit's power supply on with the switch S3; if the lamp is not lit up, switch the supply off and ask the teacher for help;

   (e) on the oscilloscope, using the *Horizontal Scale* knob, adjust the time base to the waveform being observed so that its 3 to 5 periods can be seen; <u>do not modify</u> vertical axis settings (in particular, *Vertical Scale* or *Vertical Position*);

   The distortion of the waveform that can be observed with respect to a sine wave is due to the fact that the isolation transformer is not an ideal source. It has some stray resistance and inductance that cause the voltage across its secondary winding decrease when any current is drawn by the supplied circuit.

   (f) on the computer, record the u_g waveform observed on the oscilloscope together with the measurement results presented at the bottom of the display, in a graphical form:

   - in the OpenChoice Desktop application, in the *Screen Capture* tab, click *Get Screen*,
   - click *Save As*,
   - in the *Save as format* field, select PNG,
   - choose a location for the file and give it a name,
   - accept with the mouse (<u>not with the *Enter* key</u>, as this would cause another activation of the *Save As* button).

6. Save the u_g waveform measured in channel 2 in the <u>oscilloscope's memory</u> and display it on the screen as a reference waveform:

   (a) press the *Save Recall* button and check whether the following are set in the subsequent fields (if necessary, introduce appropriate modifications using screen buttons and the *Multipurpose* knob):

   - saving waveforms (*Action*: *Save Waveform*),
   - saving to the oscilloscope's memory (*Save To*: *Ref*),
   - channel 2 as the source (*Source*: *Ch2*),
   - reference waveform A as the destination (*To*: *Ref A*);

   (b) press the screen button *Save*;

   (c) press the *R* button, then display the reference waveform A by switching (using an appropriate screen button) *Ref A* to *On*.

7. Observe and record other waveforms on the input side of the circuit:

   (a) switch the circuit's power supply off with the switch S3;

   (b) remove measurement connectors from the sockets A and B; plug measurement connectors in the sockets Z, C, E, F and H;

   (c) attach channel 1 and channel 2 probes so as to measure:

   ▪ the inverter's leg middle point potential (with respect to the ground Z) u_{mp} in channel 1,

   ▪ the rectifier's output voltage u_{rect} in channel 2;

   Voltage probe grounds (alligator clips) are shorted together in the oscilloscope and connected to the protective earth of the grid. Therefore, they must be <u>always connected to the same potential</u>. Any other connection may result in current flowing through the oscilloscope, which will damage its input circuitry!

   Before proceeding with the next sub-step, connections in the measurement set-up must be checked by the teacher!

   (d) switch the circuit's power supply on;

   (e) download and record the set of two waveforms {u_{rect}, u_g} observed on the oscilloscope together with measurement results.

Half-bridge voltages and currents

8. Observe the half-bridge leg middle point potential:

   (a) remove the input voltage waveform u_g from the screen by switching *Ref A* to *Off*;

   (b) display the channel 1 waveform by pressing the button *1*; <u>do not modify</u> time base (*Horizontal Scale* or *Horizontal Position*) or vertical axis (in particular, *Vertical Scale* or *Vertical Position*) settings in any channel;

   (c) press the button *2* to bring the channel 2 waveform back to the foreground;

   (d) change the triggering source to channel 1 by pressing the *Trigger Menu* button, then the *Source* screen button, selecting *Ch1* with the *Multipurpose* knob and confirming by pressing this knob;

   (e) set the highest possible trigger level for which oscilloscope triggering is still correct:

   ▪ increase the respective setting with the *Trigger Level* knob (the setting being indicated in the bottom right corner of the screen, following the label "Ch1") so as a vertical line, indicating the trigger level, appears above the waveforms,

   ▪ then decrease the above setting to <u>the maximum value such that</u> the message "Trig'd" (in green) is displayed <u>constantly</u> above the graticule;

   (f) without modifying <u>any other</u> settings, adjust the time base (*Horizontal Scale* knob) so that periodical variations of the u_{mp} <u>waveform</u> can be observed (i.e. <u>not</u> periodical variations <u>of its upper envelope</u> that can be already observed at this moment without changing any settings; see the frequency indicated in the ① *Frequency* field);

   <u>Before</u> proceeding with the next sub-step, consult your result with the teacher.

   (g) download and record the set of two waveforms {u_{mp}, u_{rect}} observed on the oscilloscope together with measurement results.

9. Prepare the current probe for use:

   (a) <u>carefully</u> detach the channel 2 voltage probe from the circuit and then, from the oscilloscope;

   (b) attach the current probe to the channel 2 input of the oscilloscope;

   (c) turn the current probe on which should cause the red *On* indicator on its body to light up continuously;

   If the current probe's power indicator is off or blinking, or it starts blinking while carrying out the exercise, this means that its battery is low. In such a case, do not

continue with measurements; instead, ask the teacher to replace it. Otherwise, probe indications can be erroneous.

(d) set up the probe <u>and the oscilloscope</u> according to the procedure described in an additional manual available at the laboratory stand.

10. Investigate the lamp current waveform in relation to the half-bridge leg middle point potential u_{mp}:

(a) <u>carefully</u> clamp the current probe around the wire fragments labelled as i_G and i_J so that to observe the lamp current i_{fl}, which is inaccessible in practice, as the difference of the current flowing into the lamp and the current of the capacitor C_3 (mind current directions in the electric circuit according to Fig. 1; the direction assumed as positive in the probe is indicated by an arrow on its jaws);

A current probe measures the magnetic flux induced by any current flowing in the wire around which the probe's jaws have been clamped. If the jaws are clamped around two wires, the probe will measure the sum of the respective fluxes and thus, the sum of these wires' currents. If one of these wires is introduced between the jaws in the opposite direction, its magnetic flux will have the opposite direction, too; thus, it will subtract from the magnetic flux coming from the other wire. This way, a current difference can be measured.

(b) adjust the channel 2 gain (*Vertical Scale* knob) so that the lamp current is seen in a maximum zoom, but does not extend beyond the screen; <u>do not modify</u> the zero level position (which should stay set at the middle of the graticule);

(c) download and record the set of two waveforms {u_{mp}, i_{fl}} observed on the oscilloscope together with measurement results.

Half-bridge transistor voltage and current

11. Observe the transistor Q_2 collector current i_{C2} in relation to the lamp current i_{fl} as well as to this transistor's collector-emitter voltage u_{CE2} (which, to a good approximation, is equal to the half-bridge leg middle point potential u_{mp}, see Fig. 1):

(a) save the lamp current waveform <u>in the oscilloscope's memory</u> and display it on the screen:

- press *Save Recall*, then *Save*,
- press *R*, then switch *Ref A* to *On*;

(b) transfer the current probe to clamp it around an appropriate wire so that to observe the Q_2 transistor collector current i_{C2} (mind its direction according to Fig. 1); <u>do not modify</u> any other settings on the oscilloscope;

(c) in order to make comparisons between the i_{C2} and i_{fl} waveforms easier, due to their directions opposing each other (see Fig. 1), invert the i_{C2} waveform by pressing *2*, then switching *Invert* to *Off*;

(d) change the rms value of the current measured to its magnitude (maximum value) by pressing *Measure*, selecting *Ch2*, then using the *Multipurpose* knob to uncheck *Cycle RMS* and check <u>*Minimum*</u> on the list displayed (<u>not</u> *Maximum*, as the respective waveform has been inverted);

(e) press *Menu On/Off* to close the menu and unhide measurement results;

(f) download and record the set of three waveforms {u_{mp}, $-i_{C2}$, i_{fl}} observed on the oscilloscope together with measurement results;

(g) turn off current waveform inversion by pressing *2* and switching *Invert* to *Off*;

(h) proceeding as in step 8(a), remove the i_{fl} current waveform stored in the memory from the screen.

12. * Obtain an image of transistor Q_2 operating point trajectory in its output characteristics plane, $(x, y) = (u_{CE2}, i_{C2})$, still considering that $u_{CE2} \approx u_{mp}$:

   (a) switch to the XY display mode (with the channel 1 waveform, ie.. $u_{mp} \approx u_{CE2}$, on the X-axis, and the channel 2 waveform, i.e. i_{C2}, on the Y-axis) by pressing *Utility*, then *Display* and changing *Format* to *XY*;

   (b) set the channel 1 gain (*Vertical Scale*) to 100 V/div and the channel 2 one, to 100 mA/div;

   (c) download and record the operating point trajectory plot $(x, y) = (u_{CE2}, i_{C2})$ observed on the oscilloscope;

   (d) restore the time-based mode of the display by switching *Format* back to *YT*;

   (e) restore the last time base and both channels' gain settings according to the oscilloscope image recorded previously [step 11(f)].

Voltage and current waveforms at the converter's output

13. Revert to voltage measurements in channel 2:

   (a) switch the current probe off with the switch on its body;

   (b) detach the current probe from the circuit and from the oscilloscope;

   (c) attach a 1:100 attenuation voltage probe back to the channel 2 input of the oscilloscope;

   (d) revert to the channel 2 probe setting as a voltage one by pressing *2* and selecting *Probe*, then *Voltage*;

   (e) set the channel 2 gain (*Vertical Scale* knob; the setting being indicated in the bottom left corner of the screen beside the symbol ②) as identical to the one now set for channel 1 (<u>without modifying</u> the latter).

14. Observe the lamp voltage waveform:

   (a) <u>carefully</u> transfer the channel 1 probe tip to the point F;

   (b) connect the channel 2 probe ground to point Z and <u>carefully</u> connect its tip to the point H;

   (c) set the highest possible trigger level such that oscilloscope triggering is stable [see step 8(e); it will be probably necessary to decrease this level with respect to its current setting];

   (d) enable the mathematical operation of subtraction to display the lamp voltage u_{fl} as the potential difference of $v_F - v_H$, which is equivalent to the voltage difference of $u_{FZ} - u_{HZ}$ (cf. Fig. 1):

   ▪ display the mathematical operation result waveform by pressing *M*,

   ▪ make sure that the operation of subtraction (-) is selected in the *Operation* field, while the difference between the channel 1 (the minuend, u_{FZ}) and the channel 2 (the subtrahend, u_{HZ}) waveforms, i.e. *Ch1 - Ch2*;

   (e) modify measurements as follows:

   ▪ change channel 1 waveform frequency and magnitude to its average and peak-to-peak value by pressing *Measure*, selecting *Ch1*, unchecking *Frequency* and *Maximum*, and checking *Peak-Peak* and *Mean*,

   ▪ remove channel 2 waveform frequency, minimum and peak-to-peak values by selecting *Ch2* and unchecking *Frequency*, *Peak-Peak* and *Minimum*,

   ▪ add frequency, peak-to-peak and rms measurements for the mathematical operation waveform by selecting *Math* and checking *Frequency*, *Peak-Peak* and *Cycle RMS*;

   (f) press *Menu On/Off* to close the menu and unhide measurement results;

   (g) download and record the set of three waveforms {u_{FZ}, u_{HZ}, u_{fl}} observed on the oscilloscope together with measurement results.

15. Observe the waveforms of the inverter output voltage u_{inv} and of the potentials which it results from:

   (a) <u>carefully</u> transfer the channel 1 probe tip to the point E, so that to measure the voltage u_{EZ} and, as a result of the mathematical operation, the inverter output voltage u_{inv} as the

potential difference of $v_E - v_H$, which is equivalent to the voltage difference of $u_{EZ} - u_{HZ} = u_{mp} - u_{cap}$ (cf. Fig. 1);

(b) <u>if necessary</u> (unstable waveforms on the screen), re-adjust the trigger level by setting it to the highest one such that oscilloscope triggering is stable [see step 8(e)]; do not modify <u>any other</u> settings;

(c) change one of the measurements from the rms value of the mathematical operation to its average value by selecting *Math*, unchecking *Cycle RMS* and checking *Mean*;

(d) press *Menu On/Off* to close the menu and unhide measurement results;

(e) download and record the set of three waveforms {u_{mp}, u_{cap}, u_{inv}} observed on the oscilloscope together with measurement results;

(f) press *M* several times so that to remove the mathematical operation result waveform from the screen.

16. Terminate waveform measurements in the inverter:

(a) switch the circuit's power supply off;

(b) if Section 4.3 is to be skipped, unplug the circuit from the mains;

(c) detach voltage probes from the circuit, however, <u>do not unplug</u> them from the oscilloscope.

4.3. Rectifier operation

1. * Eliminate the isolation transformer from the circuit by switching <u>both</u> switches found on the back side of the circuit's casing to "I".

2. * Adapt the circuit for simultaneous measurement of both the input voltage and current:

   (a) detach both voltage probes from the circuit;

   (b) unplug the channel 2 probe from the oscilloscope;

   (c) transfer the measurement connectors from sockets F and H to sockets A and B; remove the connector from the socket E; leave connectors in sockets Z and C;

   (d) attach the current probe to the channel 2 input of the oscilloscope;

   (e) switch the current probe on;

   (f) repeat the probe calibration procedure according to the additional manual.

3. Upload new settings to the oscilloscope:

   ▪ go to the *Get & Send Settings* tab;

   ▪ click *Open* and read the file *ustawienia_5u_prost_tbs1052.set*;

   ▪ click *Send Settings* (<u>not</u> *Send to multiple*);

   ▪ make sure that at the bottom of the screen, <u>six results</u> of various measurements are displayed, otherwise click *Send Settings* again,

   ▪ return to the *Screen Capture* tab.
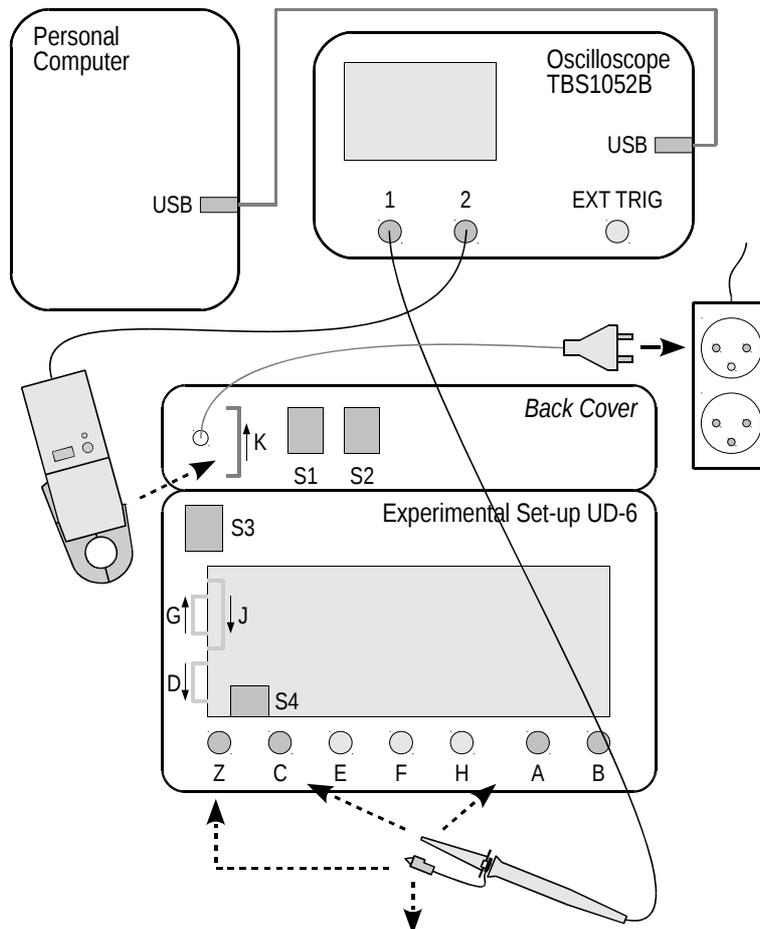
Fig. 3. Block diagram of the measurement set-up for investigating rectifier operation

Before proceeding with the next sub-step, connections in the measurement set-up must be checked by the teacher.

Special care should be taken from this point on, as the circuit will not be isolated from the supply grid! Touching any metal element will cause an electric shock with a voltage of over 300 V!

4. * Record the waveforms in the input rectifier:

   (a) switch the circuit's power supply on;

   (b) using an electrical tester pen (which should only be handled by its plastic body, without touching metal electrodes on its sides), determine which one of the points, A or B, is connected to the phase (live) wire (a red LED indicator on the pen's body lights up when a live wire is detected);

   (c) leave the voltage probe ground connector <u>unconnected</u>, while attaching its tip to the point where phase voltage has been detected, so that to measure the grid voltage u_g;

   (d) clamp the current probe around the wire led out at the back of the circuit's casing so that the instantaneous direction of the measured current drawn from the grid $i_g = i_K$ matches the instantaneous direction of the grid voltage u_g:

   - if the phase wire has been detected at point A and thus the u_g voltage direction matches Fig. 1, then the current probe should also be attached according to the i_K direction as marked in Fig. 1 and on the circuit's casing;

   - if the phase wire has been detected at point B, then the current probe should be attached in the opposite direction;

   - if the current waveform observed is inverted with respect to the voltage waveform in each respective half-cycle, this means that the current probe has been connected opposite to the input voltage, so its direction should be reversed;

   (e) download and record the waveforms of grid voltage, current drawn from the grid and instantaneous input power $\{u_g,\ i_g,\ p_g\}$ observed on the oscilloscope together with measurement results, in a graphical form (as you did before);

   (f) <u>apart from that</u>, download and record the same complete set of waveforms in a <u>numerical</u> form:

   - in the OpenChoice Desktop application, go to the *Waveform Data Capture* tab,

   - click *Select Channels* and tick all the available waveforms (CH1, CH2 and MATH),

   - click *Get Data*,

   - click *Save As*,

   - in the *Save as format* field, select CSV,

   - choose a location for the file and give it a name,

   - accept with the mouse.

   Next time, selecting channels again will not be necessary. Therefore, instead of the *Select Channels* button, the *Get Data* one may be used directly.

5. * Examine the effect of increasing the filter capacitance C_4 as observed at the circuit's input:

   (a) switch the circuit's power supply off;

   (b) by setting the switch S4 on the circuit's panel to "I," insert an additional capacitor C_4' in parallel with the capacitor C_4 already present;

   (c) switch the circuit's power supply on;

   (d) freeze the waveforms on the screen by pressing the *Run/Stop* button and <u>immediately</u> switch the circuit's power supply off;

   (e) download and record the set of waveforms $\{u_g,\ i_g,\ p_g\}$ observed on the oscilloscope together with measurement results, in a <u>graphical</u> form;

(f) <u>apart from that</u>, download and record the same complete set of waveforms in a <u>numerical</u> form [see step 4(f)];

(g) <u>imperatively</u> unfreeze the screen by pressing *Run/Stop*;

(h) switch the current probe off;

(i) detach the current probe from the circuit and from the oscilloscope.

6. * Examine the effect of increasing the filter capacitance as observed at the rectifier's output:

(a) insert the isolation transformer back into the circuit by switching <u>both</u> switches found on the back side of the circuit's casing to "II";

(b) switch over the voltage probe (both its ground connector and its tip) so that it measures the rectifier output voltage u_{rect};

(c) on the oscilloscope, hide the channel 2 waveform (the *2* button) and the mathematical operation result waveform (the *M* button);

(d) switch the circuit's power supply on;

(e) freeze the waveforms on the screen by pressing the *Run/Stop* button and <u>immediately</u> switch the circuit's power supply off;

(f) download and record the u_{rect} voltage waveform observed on the oscilloscope together with measurement results, in a <u>graphical</u> form;

(g) <u>imperatively</u> unfreeze the screen (*Run/Stop*).

7. * Terminate measurements:

(a) disconnect the additional capacitor C_4' from the circuit by setting the switch S4 to "O";

(b) unplug the circuit from the mains;

(c) detach the voltage probe from the circuit, however, <u>do not unplug</u> it from the oscilloscope.

Results

5. Result Elaboration and Analysis

5.1. Ballast operation

Electronic ballast as a multi-stage power converter

1. In Part 1 of the report, insert oscilloscope images of voltages and currents in the ballast circuit recorded in steps 4.2/5-15.

2. Based on appropriate oscilloscope images, for each the following waveforms at key points of the circuit:

   ▪ at the input of the rectifier, i.e. at the grid terminals, u_g (cf. Fig. 5-23 in Ref. D),

   ▪ at the output of the rectifier, equivalent to the input of the inverter, u_{rect} (cf. Fig. 5-23 in Ref. D; the image should be used that shows how this waveform varies with a grid-related frequency),

   ▪ at the output of the inverter, i.e. across the half-bridge diagonal, u_{inv} (cf. u_A in Fig. 8 in Ref. C [22]),

   ▪ at the output of the ballast, i.e. through the lamp i_{fl} (cf. i_{la} in Fig. 8 in Ref. C [22]),

   determine or read out:

   ▪ its shape (what typical one it mostly resembles, in what way it is different from an ideal one),

   ▪ its frequency (a *Frequency* indication),

   ▪ its alternating component magnitude, i.e. half of its peak-to-peak value (a *Peak-Peak* indication),

   ▪ its direct component level, i.e. its average value (a *Mean* indication).

   Due to the relatively small amplitude of the u_{rect} waveform, its frequency may be indicated erroneously on the oscilloscope (especially if an "?" sign is displayed beside the value). This should be determined by comparing the u_{rect} waveform to the u_g waveform, whose frequency has been read out.

In case the indication on the oscilloscope is doubtful, the frequency of the u_{rect} voltage must be calculated from the frequency of u_{g}.

Enter your results into the table in Part 1 of the report.

3. Based on your results from step 2, state whether an alternating and a direct component are present in each of the analysed waveforms. In this respect, if the value of the smaller of the two components is less than the measurement uncertainty of the other one, the former should be considered negligible. On this basis, in the last two rows of the table, enter:

- ▪ "absent" if a given component is negligible,
- ▪ "dominant" if neither component can be neglected, but a given component is at least two times greater than the other one,
- ▪ "present" if a given component is neither negligible or dominant.

The relative gain uncertainty of the oscilloscope used (for gain values that were applied) was 3%. Additionally, the uncertainty of the voltage probe was 3.6% while that of the current probe was 1%.

4. Complete Part 1 of the report.

Half-bridge inverter operation

5. Fill in Part 2 of the report.

Transistor operation in the inverter

6. * Superpose the operating point trajectory of the transistor Q_2 on the safe operating area diagram of this device:
   (a) copy the safe operating area diagram from the transistor's data sheet and paste it into a new LibreOffice Draw document;
   (b) into the same document, import the image of the operating point trajectory of the transistor Q_2 in its output characteristics plane, $(x, y) = (u_{\text{CE2}}, i_{\text{C2}})$ (the oscilloscope image recorded in step 4.2/12);
   (c) using the appropriate function (*Crop Image* icon or *Format ▸ Image ▸ Crop* from the menu), crop the image imported so that it contains the graticule area together with both axes information displayed below;
   (d) with the imported image selected, in the side panel (display it from the *View* menu if it is hidden), choose *Properties ▸ Image* and set *Transparency* to 35%;
   (e) place the images one on another while aligning the origins of both systems of coordinates and matching both plots' scales (by changing the dimensions of the operating point trajectory image; operate the mouse with the *Shift* key pressed to modify X and Y dimensions independently);
   (f) select both images and paste in Part 3 of the report <u>as a bitmap</u>.
7. Fill in Part 3 of the report.

Interaction with the fluorescent lamp

8. Fill in Part 4 of the report.

The crest factor is defined for any physical quantity x as

$$k_{cx} \stackrel{\Delta}{=} \frac{X_{\text{m}}}{X_{\text{rms}}} \tag{5.1}$$

where X_{m} is its maximum value and X_{rms} is its rms value.

5.2.   Rectifier and electromagnetic compatibility

Results obtained with the oscilloscope

1.   * In Part 5 of the report, insert oscilloscope images of voltage, current and power at the rectifier's input as well as those of its output voltage recorded in steps 4.2/7 and 4.3/4-6.

2.   * Based on appropriate oscilloscope images:

(a) read out:

■   the peak-to-peak (*Peak-Peak* indication) and average (*Mean* indication) value of the rectified voltage u_{rect} ($U_{\text{rect(pp)}}$ and $U_{\text{rect(av)}}$, respectively),

■   the average input power (drawn from the grid) P_{g}, i.e. the average value (*Mean* indication) of the instantaneous input power, thus of the product of the grid voltage u_{g} and the current drawn from the grid i_{g} (the mathematical operation waveform, *M*),

The oscilloscope did not have any information about whether the mathematical operation waveform represented any power or what kind of power it was; therefore, it indicated this waveform's unit as VA, which only reflects the general fact that some voltage waveform was multiplied by some current waveform. However, it is known that (provided measurements were carrier out according to the manual) the average value was measured of instantaneous power, yielding average power; therefore, the result should be shown in an SI unit of this very physical quantity.

■   the rms values (*RMS* or *Cycle RMS* indication) of the grid voltage $U_{\text{g(rms)}}$ and of the current drawn from the grid $I_{\text{g(rms)}}$,

■   the grid voltage fundamental frequency $f_{\text{g(1)}}$ (*Frequency* indication);

(b) calculate:

■   the ripple factor of the rectifier's output voltage $r_{u\text{rect}}$, which parameter can be defined for any physical quantity x as

$$r_x \overset{\Delta}{=} \frac{X_{\text{pp}}}{X_0} \tag{5.2}$$

where X_{pp} is its peak-to-peak value and X_0 is its direct component, identical to its average value (alternative definitions exist, with the one based on the rms value being the most popular one),

■   the rectifier's apparent input power S_{g} (Manual 0, Ref. D),

■   the power factor at the rectifier's input λ (using its definition; Manual 0, Ref. D).

Enter the values obtained into the table in Part 5 of the report.

Input current spectrum

3.   * Launch and set-up the computing environment:

(a) run the numerical computing package Octave;

(b) click the *Browse Directories* icon and change the working folder to the one containing oscilloscope data recorded using OpenChoice Desktop;

(c) move the necessary Matlab script files to the working folder or add the path to these files to the *path* variable by executing the command:

```
addpath('scripts_path');
```

4. * Based on the data recorded in the numerical form in step 4.3/4 for the initial value of the rectifier's filter capacitance $C_{4(ini)}$ (capacitor C_4 alone), obtain spectra and selected parameters of grid voltage and current:

   (a) read data recorded in the numerical form (CSV format) in the appropriate file, by executing the command:

   ```
   OscRecord=oscreadtbs('file_name.csv');
   ```

   (b) to simplify further result processing, create two variables and assign indices of the recorded grid voltage u_g and current drawn from the grid i_g waveforms to these variables by executing the commands:

   ```
   iUg=oscchid(OscRecord,'channel_label_ug')
   iIg=oscchid(OscRecord,'channel_label_ig')
   ```

   The parameters *channel_label_ug* and *channel_label_ig* represent labels of oscilloscope channels where the u_g and i_g waveforms were measured, respectively. If probes were connected in accordance with this manual (step 4.3/4), then these were the channels 1 and 2 which the oscilloscope used labels as *CH1* and *CH2*, respectively. If in doubt, all the waveforms contained in the file read can be plotted by executing the command oscplotscreen(OscRecord); based on their shapes and the graph legend, a corresponding meaning and label can be established for each of them.

   (c) obtain spectra of both the above waveforms by executing the commands:

   ```
   [Spectr_ig,ifg1]=oscspectr(OscRecord,iIg,fg1);
   [Spectr_ug,ifg1]=oscspectr(OscRecord,iUg,fg1);
   ```

   where the grid fundamental frequency value $f_{g(1)}$ should be substituted for *fg1*.

   The *oscspectri* function crops input data (the structure *OscRecord*) so that they contain an integer number of periods corresponding to the frequency *fg1* and then, using the Fast Fourier Transform, calculates the frequency spectrum for the specified waveform. The variable *ifund* will contain the index corresponding to the frequency *fg1* in output vectors.

   (d) determine the total harmonic distortion of the current drawn from the grid $d_h(i_g)$ by executing the command:

   ```
   dhig=spectrthd(Spectr_ig,ifg1)
   ```

   (e) calculate the phase shift $\varphi_{g(1)}$ between the fundamental components of grid voltage and current by computing the phase difference (expressed in radians; the result can be converted into degrees using the function *rad2deg*):

   ```
   phig1=Spectr_ug.phi(ifg1)-Spectr_ig.phi(ifg1)
   ```

   (f) enter the numerical results obtained in sub-steps (d) and (e) into the table in Part 5 of the report;

   (g) save the obtained time-domain and frequency-domain data for future comparison by copying them to new variables:

   ```
   Spectr_ig_C4ini=Spectr_ig;
   OscRecord_C4ini=OscRecord;
   ```

5. * Repeat step 4 for the file recorded in step 4.3/5 to obtain analogous results for the increased filter capacitance $C_{4(incr)}$ (capacitor C_4' added), while:

   ▪ skipping sub-step (b) as channel numbers should not have changed;
   ▪ copying data in sub-step (g) to different variables whose names would reflect the increase in capacitance: :Spectr_ig_C4incr and OscRecord_C4incr.

6. * Get plots enabling the current drawn from the grid to be compared for two filter capacitance values:

    (a) obtain a comparative graph of the current drawn from the grid together with the grid voltage, over an interval of one period, by executing the command:

    ```
    plot5u_iuTime(OscRecord_C4ini,OscRecord_C4incr,iUg,iIg)
    ```

    (b) obtain a comparative graph of spectra of the current by executing the command:

    ```
    plot5u_iSpectr(Spectr_ig_C4ini,Spectr_ig_C4incr)
    ```

    (c) copy both plots and paste them in the appropriate spaces provided in Part 5 of the report.

7. * Complete Part 5 of the report.

E

Information

6. Required Knowledge

6.1. Prerequisites

- Schematic and general operating principle of the half-bridge fluorescent lamp electronic ballast
  (Ref. C)

6.2. Test scope

1. Advantages and disadvantages of BJTs in power electronics. Current fields of application.
   (see Ref. A and Manual 0, Ref. H, Section 3.1.2)

2. Half-bridge low-pressure fluorescent lamp electronic ballast: block diagram (disregarding optional blocks), voltage and current waveforms at characteristic points of the circuit, drawbacks of the standard ballast and advantages of the electronic ones.
   (Refs. B and C; report)

3. Voltage-fed half-bridge inverter: simplified electrical schematic (without control circuitry details); leg middle point voltage, output (lamp) current, semiconductor switch current waveforms. Resonant circuit: components (before and after lamp ignition) and role; inductor's roles. Required transistor ratings in relation to the input and output voltages or to the output current of the half-bridge.
   (Ref. B and C; report)

4. Single-phase diode bridge rectifier: circuit schematic, switches conducting and not conducting depending on input voltage direction (sign); input voltage, input current and output voltage waveforms with and without the filter capacitor (Figs. 5-8 and 5-23).
   (see Ref. D)

7. References

[1]   Benda V., Gowar J., Grant D. A.: *Power Semiconductor Devices: Theory and Applications.* Wiley, 1999. ISBN 0-471-97644-X.

[2]   Mohan N., Undeland T. M., Robbins W. P.: *Power Electronics: Converters, Applications, and Design.* 3rd Ed. Wiley, 2003. ISBN 0-471-22693-9.

[3]   Erickson R. W., Maksimović D.: *Fundamentals of Power Electronics. Second Edition.* Springer, 2001. ISBN 0-792-37270-0.

[14]   *Power Semiconductor Applications.* Philips Semiconductors, 1994.

[18]   Bairanzade M.: *Electronic Lamp Ballast Design.* Motorola, 1995. Application Note AN1543/D.

[22]   Op het Veld J. H. G.: *Self Oscillating Circuit for CFL10W and CFL18W Lamps.* Philips Electronics, 1999. Application Note AN99065.