



POWER DEVICES AND SYSTEMS LABORATORY

Exercise 5^B

Bipolar Junction Transistor Multi-Stage Off-Line Converters

Indicatory work plan

15'	30'	45'	1 ^h	1 ^h 15'	1 ^h 30'	After Class
4.2/1-6	4.2/7	4.2/8-11		4.3/1-3	4.3/4-7	5

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Łódź 2011

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Exercise Introduction

1. Exercise Aim and Plan

In this part of the exercise investigation of the power Bipolar Junction Transistor is continued. A typical electronic ballast for a Compact Fluorescent Lamp (CFL) will be used as an application example. BJTs applied in this circuit belong to the high-voltage but small-power device group (rated power of the order of 0.1 to 1 W). Measurement results will be used to analyse how a particular transistor has been selected for the investigated circuit.

The chosen application creates an opportunity to get acquainted (at the level of functional elements) with a typical structure of modern electronic cycloconverters. Instead of complex single-stage structures used in the past, we deal with a two-stage structure, which is, however, formed by two very simple converters: a rectifier and an inverter. The operation of these circuits will be analysed, including interaction with the supply network. On this occasion, one of the typical working configurations of power semiconductor devices will be presented—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, Why electronic ballasts? ... Compact and light weight, Electronic ballast topologies, The half bridge inverter, Voltage fed half bridge inverter	2.2, 2.3	[18] Main Purpose, Fluorescent Lamp Operation, Controlling the Fluorescent Lamp, Half Bridge Topology Analysis without Start-up Sequence, Half Bridge Design, Breakdown Voltage	

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

Section 6.6. of [Ben] is found in the document already published as Refs. AB for Manual 5^A.

Ref. [14] has already been published under Exercise 6.

3. Rectifiers

3.1. Recommended reading

Ref.	Textbook	Excerpt	Equivalent in the Polish Manual	Complementary Reading	Complements in this Manual
C	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		
D	Eri	16.3.2, 16.6, 16.6.1	3.3.b, 3.3.c		

4. Measurements

4.1. The laboratory circuit

Ballast under investigation

The subject of this experiment is a typical, low-cost, compact fluorescent lamp with an electronic ballast. The nominal power of this lamp is $P_n = 11 \text{ W}$ and the nominal voltage is $U_n = 230 \text{ V}$.

The complete schematic diagram of the ballast is shown in Fig. 1. As can be seen (see Ref. B) belongs to the half-bridge circuit family. The half-bridge consists of two transistors T_1 and T_2 (the active leg) and the capacitor C_1 (the passive leg). Thus, the bridge is asymmetric – there is no capacitor connected to the ground. In the diagonal of the bridge, the lamp with the capacitor C_3 , the inductor L and the primary winding of the transformer L_{tra} are connected.

To simplify the analysis it is assumed that the point Z is the ground of the circuit. Thus, the voltage potential at point C is equal to the rectified voltage supplying the inverter, which will be denoted as u_d .

The different functional elements (according to Fig. 4 in Ref. B [14]) are:

- rectifier – the diode bridge $D_1...D_4$;
- low-pass (DC) filter – the capacitor C_6 ;
- DC/AC inverter – the half-bridge T_1, T_2, C_1 ;
- actual ballast – the inductor L .

We can also discern:

- start-up circuit – the resonant circuit L, C_3 ;
- output current shaping circuit – the resonant circuit L, C_1 ;
- initial heating circuit – the capacitor C_3 .

The schematic shows that the circuit is voltage-fed as the rectified voltage u_d is applied directly from the rectifier's filter output to the input of the inverter. Although the half-bridge is asymmetric, the behaviour of the circuit is nearly the same as that of the circuit presented in Ref. B [18]. One

4.2. Two-stage AC/AC converter

Circuit preparation

In order not to waste time, proceed with next steps in parallel with step 1.

1. Turn on the computer. After log-on is complete, set up the connection to the oscilloscope according to the additional manual available at the laboratory stand.
2. Turn on the oscilloscope and introduce the following settings:

Most of the buttons of the HM1507 oscilloscope has twofold or threefold action:

- (1) activated by pressing the button for a short period of time (a basic function),
- (2) activated by pressing the button and holding it until a beep sound is heard (a function marked with **■**),
- (3) activated by simultaneously pressing the button together with an adjacent one (a function marked with **●●**).

If the oscilloscope does not act as described in this manual, first make sure that an alternative function of a given button has not been activated by mistake.

- digital storage operation mode (if not already enabled) – press and hold the *HOLD* button until a beep sound is heard and one of the *STOR. MODE* indicators is lit;
 - periodic refresh operation mode – *STOR. MODE* **▲**/**▼** buttons, select *RFR*;
 - both channel waveforms displayed – the *DUAL* button;
 - DC coupling (in both channels) – the *AC DC* button whose state is indicated on the display next to the Y1 and Y2 channel labels: “=” stands for DC coupling, “~” stands for AC coupling;
 - voltage probe 1:10 attenuation taken into account (in both channels) – the *AC DC* button holded (when 1:10 attenuation is taken into account, this is indicated by the probe symbol **1** displayed next to the channel symbol, Y1 or Y2);
 - waveform inversion off (in both channels) – the *INV* button (when a waveform is inverted, this is indicated with a bar over the channel symbol, Y1 or Y2);
 - line voltage triggering – the *TRIG. MODE* button, select “~” (exactly this setting, not any other one);
 - same zero levels (**⊥** marks) for both channels, in the middle of the display – the *Y-POS* knobs.
3. Switch both switches found on the back side of the case to II.
 4. Set the power supply switch on the circuit’s panel to “O”. Plug the circuit to the mains through an additional extension cord.
 5. Check whether the lamp lights up after power supply is turned on with the switch on the circuit’s panel; if not, turn the power off and ask the teacher for help.
 6. Turn the power off using the switch on the circuit’s panel.

Voltage and current waveforms

7. Investigate the waveforms observed at the input of the circuit:
 - (a) Connect the channel 1 probe to the circuit so as to measure the input voltage u_i . Any other probes should remain unconnected to the circuit.

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

- (b) Turn on the power supply.

- (c) Display only the channel 1 waveform on the oscilloscope (the *CHI* button) and adjust:
- the time base so that 2 to 4 periods of the waveform can be seen on the display,
 - channel 1 gain so that the waveform fills the display maximally but does not extend beyond it (do not change the zero level position using the *Y-POS* knob).

The waveform is distorted with respect to a sine wave. This follows from the fact that the isolation transformer is not ideal: the voltage across its secondary winding falls down when a current is drawn from it by the supplied circuit.

- (d) Save the u_i waveform measured in channel 1 in the oscilloscope's memory:
- shortly press *REFERENCE* several times so that only the *I* indicator becomes on,
 - then, press *REFERENCE* again and hold until a beep sound is heard,
 - after which the waveform should become visible in the screen background (this can be checked by slightly moving the channel 1 waveform with the *Y-POS* knob, after which the previous zero level position in the middle of the screen should be immediately restored).
- (e) Turn off the power supply with the switch on the circuit's panel.
- (f) Detach both connectors of the probe from the circuit
- (g) Attach the channel 1 and channel 2 probes so as to measure:
- the rectifier output voltage u_d in channel 1,
 - the inverter active leg middle point voltage potential (with respect to the ground *Z*) u_{inv} in channel 2.

Voltage probe grounds (alligator clips) are shorted together in the oscilloscope and connected to the supply network's protective earth. They must be therefore always connected to a same potential. Any other connection may result in current flowing through the oscilloscope, which will damage its input circuitry!

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

- (h) Turn on the power supply.
- (i) Display both channel 1 and channel 2 waveforms by pushing *DUAL*. Without changing any other settings, set the same gain and zero level for channel 2 as they are set for channel 1. If the u_d waveform overlaps the u_{inv} one, slightly move its zero level only to the extent that prevents the two waveforms from overlapping.
- (j) Download the set of 3 waveforms $\{u_d, u_{inv}, u_i\}$ observed on the oscilloscope to the computer: push *Read* in the SP107 application. Ensure that each of the 3 waveforms is visible. Save the waveforms to a file using the MES format (which should be used all throughout this exercise).

Waveforms stored in the oscilloscope's memory (i.e. saved using the *REFERENCE* button) are downloaded as *Ref I* (channel 1 saved waveform) and *Ref II* (channel 2 saved waveform). Only those waveforms are downloaded for which the appropriate *I* or *II* indicator beside the *REFERENCE* button is on.

8. Investigate the half-bridge voltage waveforms:
- (a) Hide the input voltage u_i waveform saved in the oscilloscope's memory: press *REFERENCE* several times until both *I* and *II* indicators go out.
- (b) Select DC level triggering – set *TRIG. MODE* to *DC* and the trigger source to the active leg middle point potential u_{inv} – press the *TRIG* button several times until the proper channel indicator lights up.
- (c) Set the highest possible trigger level for which triggering occurs correctly – adjust the *LEVEL* knob up as long as the *TR* indicator is on.

- (d) Adjust the time base so that the periodical changes of the u_{inv} waveform can be observed (the changes of the u_{inv} waveform, not of its upper envelope which can be already observed at this moment without changing any settings). Do not modify any other settings. Consult your result with the teacher.
 - (e) Download and save the set of 2 waveforms $\{u_d, u_{inv}\}$ observed on the oscilloscope.
9. Investigate current waveforms in relation to the active leg middle point voltage potential u_{inv} :
- (a) Detach the channel 1 voltage probe from the circuit and then from the oscilloscope. Attach a current probe in its place.
 - (b) Turn the current probe on. The red *ON* indicator should light up continuously.
 - (c) Set up the probe according to the procedure described in the additional manual available at the laboratory stand.

The current/voltage conversion factor of the current probe is $100 \text{ mV/A} = 1:10$; the value measured on channel 1 will therefore be the current value in amps provided the 1:10 attenuation is still taken into account (see step 2).

When measuring current, special care must be taken not to tear wires out of the printed circuit board! The current probe should be clamped and detached gently and kept in hand for all the time the measurement is performed.

- (d) Carefully clamp the current probe around the wires led out labelled as i_G and i_H so that to observe the inaccessible lamp current i_{fl} as the difference of C_1 and C_3 capacitor currents (observe the current direction according to Fig. 1; the current direction assumed as positive is indicated on the probe jaws).

A current probe measures magnetic flux induced by the current flowing in the wire around which the jaws of the probe have been clamped. If the jaws are clamped around two wires, the probe will measure the sum of fluxes and thus, the sum of currents. If one of these wires is introduced inside the jaws in the opposite direction, its magnetic flux will also have the opposite direction, so it will subtract from the magnetic flux coming from the other wire; this way, we can measure a current difference.

In the circuit under investigation, rapidly changing voltages of high amplitude are present. This causes emission of considerable electromagnetic field directly from the circuit. This field interferes with the current probe which can be observed by slightly changing its orientation. In order to minimise the influence of this phenomenon on measurement results, the probe should be held beside the circuit, at some distance (as far as wires enable it).

- (e) Adjust the channel 1 gain so that the lamp current is zoomed maximally but does not extend beyond the screen. Do not change the zero level position in the middle of the screen.
- (f) Store the current waveform in the oscilloscope's memory [see step 7(d)].
- (g) Carefully transfer the current probe to clamp it around the appropriate wire so that to observe the T_1 transistor collector current $i_{C,T1}$ (mind the current direction).

Due to the disturbances mentioned above, the probe should be positioned at such an angle that in time intervals where transistor current is not flowing, the waveform on the screen is seen conforming to the reality, as a horizontal line close to the zero level.

- (h) Invert the waveform coming from the probe (the *INV* button for the appropriate channel, see step 2) so that the $i_{C,T1}$ current is observed with the same sign as the lamp current i_{fl} . (with respect to the $C_1 - L - T_1$ loop). Do not modify any other settings.
 - (i) Download and save the set of 3 waveforms $\{i_{C,T1}, u_{inv}, i_{\text{fl}}\}$ observed on the oscilloscope.
 - (j) Imperatively disable the invert function for the current probe channel (*INV*).
 - (k) Detach the current probe from the circuit and turn it off.
10. Investigate the lamp voltage waveform:
- (a) Hide the lamp current i_{fl} waveform [see step 8(a)].

- (b) Turn off the power supply of the circuit.
- (c) Attach the voltage probe back to channel 1.
- (d) Revert the gain of the channel to which the current probe was connected to the same setting as for the other channel. The zero levels should still be set at the middle of the screen.
- (e) Attach voltage probes to the circuit:
 - both probe grounds to point Z,
 - channel 1 tip to point H,
 - channel 2 tip to point F.
- (f) Turn on the power supply.
- (g) Set the highest possible trigger level for which triggering occurs correctly [see step 8(c); it may be necessary to decrease it with respect to its current setting].
- (h) Invert the u_{FZ} waveform (*INV*).
- (i) Enable the sum function *ADD* (buttons *DUAL* and *CH II* pushed simultaneously). A successful accomplishment of this action will be indicated with a “+” symbol between the channel labels Y1 and Y2. Otherwise, first de-activate the function mistakenly activated and then try to push the respective buttons again.

As the waveform shown on the screen is a result of adding the inverted u_{FZ} voltage to the u_{HZ} voltage,

$$u_{HZ} + (-u_{FZ}) = u_{HZ} - u_{FZ} = v_H - v_F = u_{HF} = u_{\Pi} \quad (4.1)$$

the voltage across the lamp u_{Π} is currently measured.

- (j) Download and save the u_{Π} waveform observed on the oscilloscope screen.
 - (k) Imperatively disable both the invert (*INV*) and the sum (*ADD*) functions.
11. Switch the power off and unplug the circuit (the additional extension cord's plug) from the mains.

4.3. Rectifier operation

1. * Eliminate the isolation transformer from the circuit by switching both switches at the back of the circuit's casing to I.

Warning!

Do not plug the circuit (the additional extension cord) into the mains at this moment.

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

2. * Adapt the circuit for simultaneous measurement of both the input voltage and current.
 - (a) Disconnect both voltage probes from the circuit. Detach the channel 2 probe from the oscilloscope.
 - (b) Insert two measurement connectors to A and B binding posts (leaving the connector from the Z binding post in its place.)
 - (c) On the oscilloscope, select mains voltage triggering (*TRIG. MODE*: "~").

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

- (d) Plug the circuit (the additional extension cord) into the mains and switch the power on.

When using the electrical tester pen used in the following step, grab it only by its plastic parts and under no circumstances touch the metal electrodes on its sides!

- (e) Use the electrical tester pen to determine which one of the points A and B is connected to the phase (live) wire. (When a live wire is detected, the red LED indicator on the pen lights up.)
 - (f) Switch the power off.
 - (g) Attach the voltage probe ground connector to the protective earth pin (PE) of the extension cord. Use the short wire with an alligator clip available on the laboratory stand that has wider jaws than that of the voltage probe. Attach the probe tip to the point where phase voltage has been detected. This way, the input voltage u_i is measured.
 - (h) Attach the current probe to channel 2 of the oscilloscope and turn on the probe. If necessary—in case the waveform is not found at the channel 2 zero level—repeat the current probe set-up according to the additional manual.
3. * Record the waveforms in the input rectifier:
 - (a) Switch the power on.
 - (b) Adjust the time base to the mains voltage frequency so that its 3 to 5 periods can be observed.
 - (c) Clamp the current probe around the i_K wire led out at the back of the circuit's case so that the instantaneous direction of the measured input current $i_i = i_K$ matches the instantaneous direction of the input voltage u_i :
 - if the phase wire has been detected at point A and thus the u_i voltage direction matches Fig. 1, then the current probe should also be attached according to the i_K direction in Fig. 1 and on the circuit's case;
 - if the phase wire has been detected at point B, the current probe should be attached in the opposite direction.
 - (d) Adjust the both channel gains to the observed waveform amplitudes. The zero levels of both channels should still be set in the middle of the display.

- (e) If the current waveform observed is inverted with respect to the voltage waveform in a given half-cycle, it means the current probe has been connected opposite to the input voltage so its direction should be reversed.
 - (f) Download and save the input voltage and current waveforms $\{u_i, i_i\}$ observed on the oscilloscope.
 - (g) Switch the power off and unplug the circuit (the additional extension cord, not the circuit's plug) from the mains.
4. * Examine the effect of increasing the filter capacitance C_6 on the circuit's input:
- (a) In parallel with the capacitor C_6 of 2,2 μF , i.e. between points Z and C, connect an additional capacitor as indicated by the teacher. Mind the proper polarity according to the “-” mark on the capacitor's case and to the schematic diagram of the circuit (Fig. 1).

Before proceeding with the next sub-steps, the way the capacitor has been inserted must be checked by the teacher!

- (b) Plug the circuit into the mains and switch the power on.
 - (c) Freeze the waveforms on the display (the *HOLD* button). Switch the power off.
 - (d) Download and save the input voltage and current waveforms $\{u_i, i_i\}$ observed on the oscilloscope.
 - (e) Imperatively unfreeze the waveforms (the *HOLD* button).
 - (f) Detach the current probe from the circuit and turn it off. Detach the current probe from the oscilloscope.
 - (g) Insert the isolation transformer back into the circuit by switching both switches at the back of the circuit's casing to II.
5. * Examine the effect of increasing the filter capacitance C_6 on the rectifier's output.
- (a) Switch over the voltage probe so that it measures the u_d voltage.
 - (b) Display only the waveform from channel 1 (*CH 1*).
 - (c) Switch the power on.
 - (d) Freeze the waveform on the display (*HOLD*). Switch the power off.
 - (e) Download and save the u_d voltage waveform.
 - (f) Imperatively unfreeze the display (*HOLD*).
6. * Unplug the circuit from the mains.

Warning! Failure to complete the following step may lead to electric shock due to the charge accumulated in the capacitor.

7. * Switch over the voltage probe connectors directly to the leads of the additional capacitor and check whether it is indeed discharged (a constant waveform at the appropriate channel zero level, indicated by the zero level mark, should be observed on the oscilloscope). If so, detach the capacitor from the circuit. If not or in case of doubt, ask the teacher for help.

5. Result Elaboration and Analysis

5.1. Investigated circuit as a multi-stage electronic power converter

1. Create a schematic diagram of the circuit investigated based on Fig. 4 in Ref. B [14] and the description in Section 4.1. Disregard the isolation transformer since it was only present for safety reasons and is not present in real-life circuits.
2. Based on the oscilloscope images recorded in steps 4.2/7–9, determine the basic parameters of waveforms present at different points of the circuit:

Use cursors in the SP107 application to read out values of voltage, current and time intervals. Voltage values at time points indicated by the cursors are displayed in the *Cursor* frame, in *CH I* and *CH II* rows. In the *CI-CII* column, the voltage difference between cursor 1 and cursor 2 is displayed. In the *dt* and *1/dt* fields below, the time interval between the cursors and its reciprocal are indicated, respectively. In order to move the cursors along the Ref I and Ref II waveforms that come from the oscilloscope's memory, check the *Ref* field.

The oscilloscope took into account the current/voltage conversion factor of the current probe [provided it has been set up properly; see step 4.2/9(c)]. Thus, current values can be read out directly: a value read out using a cursor will represent a current expressed in amps.

- (a) at the input of the rectifier u_i (the set of waveforms recorded in step 4.2/7, cf. Fig. 5-23 in Ref. C):
 - shape (what typical one does it resemble most? what distortions can be observed if any?),
 - amplitude (magnitude) $U_{i(m)}$,
 - frequency f_i ;
- (b) at the output of the rectifier u_d (the set of waveforms recorded in step 4.2/7, cf. Fig. 5-23 in Ref. C):
 - shape (see above),

- average rectified value $U_{d(av)}$, which can be considered to be the average of the peak $u_{d(pk)}$ and valley $u_{d(val)}$ values,
 - ripple frequency f_d ,
 - ripple peak-to-peak value $U_{d(pp)}$;
- (c) inside the inverter $u_{inv} = u_{CE,T2}$ (the set of waveforms recorded in step 4.2/8):
- shape,
 - amplitude (high level) $U_{inv(m)}$,
 - frequency f_{inv} ;
- (d) at the output of the inverter $i_o = i_{fl} = i_H - i_G$ (the set of waveforms recorded in step 4.2/9):

To be precise, the output quantity of the inverter is the bridge diagonal current i_H . However, it follows from the operating principle of the considered circuit that after lamp ignition the i_G current is significantly lower than the lamp current i_{fl} and has no influence on circuit operation. On the other hand, the lamp current i_{fl} is of great significance, which justifies considering it as the output quantity. Strictly speaking, the lamp current constitutes the output of the ballast (i.e., the entire circuitry that surrounds the lamp) and not of the inverter itself.

- shape,
 - amplitude (magnitude) $I_{o(m)}$,
 - frequency f_o .
3. Include all the results obtained step 2 in the schematic diagram from step 1.
4. Based on the schematic diagram with the parameters written in, prove that the investigated circuit is a multi-stage power converter.

5.2. Operation of BJTs as switches in the half-bridge inverter

1. In the SP107 application, open the file containing the waveform of the T_2 transistor collector-emitter voltage $u_{CE,T2}$, recorded in step 4.2/8. Using a cursor, determine the peak value of this voltage $u_{CE,T2(pk)}$.
2. In the SP107 application, open the file containing the waveform of the T_1 transistor collector current $i_{C,T1}$, recorded in step 4.2/9. Using a cursor, determine the peak value of this current $i_{C,T1(pk)}$.
3. Using the datasheet of the 13001 transistor enclosed, analyse how the ballast designer has chosen this particular device for his circuit:

It follows from the circuit's operating principle that both transistors work in almost exactly the same conditions. Therefore, one can analyse some of the parameters as determined for the T_1 transistor while others as determined for the T_2 transistor.

- (a) Compare the working peak value of the collector-emitter voltage $u_{CE,T2(pk)}$, obtained in step 1, to the maximum rated voltage; estimate the resulting safety margin. Mind the correct choice of the datasheet parameter (see Ref. A of Manual 5^A, Section 6.2.2, Ref. B [18] p. 10).

As can be seen in Fig. 1, there is a resistor and a coil between base and emitter of the T_1 transistor in the investigated circuit; in the steady state, the coil has a zero impedance (forming a short-circuit). In the case of the T_2 transistor, although there is an additional serial capacitor, when the transistor is turning on or turned on, there is a negative base-emitter voltage forced which causes the D_5 diode to conduct (form a short-circuit).

- (b) Compare the working peak value of the collector current $i_{C,T1(pk)}$, obtained in step 2, to the continuous maximum rated current; calculate the resulting safety margin.
 - (c) In the Safe Operating Area diagram given in the datasheet, localise and mark the extreme operating points of the transistor in static states: the peak current in the conducting state $i_{C,T1(pk)}$ and the peak voltage in the blocking state $u_{CE,T2(pk)}$. (The voltage drop in the conducting state and the leakage current in the blocking state are unknown and should be considered negligible.) Determine if these points fit in the Safe Operating Area.
 - (d) Based on the current gain β_F characteristic given in the datasheet (as h_{FE}), determine the approximate value of this gain for the transistor under investigation at the peak collector current $i_{C,T1(pk)}$ (assume the lower of the voltage drops, $U_{CE} = 1,5 \text{ V}$). Calculate an approximate base current I_B value that the transformer in the investigated circuit has to deliver in order to correctly drive the transistors.
4. Search the offers of semiconductor device retailers and find one, possibly the cheapest one, transistor of each type: a BJT, a MOSFET and an IGBT, whose parameters are close to those of the 13001 transistor (rated voltage—see Ref. A of Manual 5^A, Section 6.2.2; rated current). Print out or save web page screenshots showing the data of the transistors found.

It is possible for some of the parameters to be higher than those for the 13001 transistor. They cannot be significantly lower, however, since such devices would not be suitable as replacement parts. The rated current criterion should be applied in first place, and only then, the rated voltage criterion.

Determine the price relations between the transistors found. Do they justify the presence of BJTs in modern power electronic circuits despite the obvious advantages of newer transistors (MOSFETs, IGBTs)?

5.3. Investigated circuit as a fluorescent lamp ballast

Starting Scilab

1. Run the Scilab numerical computation package.
2. Load the script containing necessary functions by executing the command:

```
exec('script_path\cw5b.sce');
```

where *script_path* is the path for the *cw5b.sce* file.

3. In order not to enter the full path for measurement data files (SP107 files) every time they are accessed, it is possible to change the working directory to the one containing them by executing the command:

```
cd('measurement_folder_path')
```

Parameter determination and analysis

4. Based on the lamp current waveform i_{fl} recorded in step 4.2/9, compute the rms value $I_{fl(rms)}$, the peak value $I_{fl(pk)}$ and the crest factor k_{ci} of this current:

- (a) in the SP107 application, open the file containing the i_{fl} waveform (the set of waveforms recorded in step 4.2/9);
- (b) save data to a text file: *Data* ► *Save* from the menu, select the *Table (*.tab)* format;
- (c) in Scilab, load the data from the TAB file saved into *header* and *data* matrices by executing the command:

```
[header,data]=wczytaj_sp107('file_name.tab');
```

- (d) display the file's header by typing:

```
header
```

and determine which column of the *data* matrix contains values of time and which one—values of lamp current i_{fl} (refer the labels to the waveforms observed in the SP107 window, to your notes from the measurements or to the oscilloscope channel configuration description of step 4.2/9);

- (e) calculate the rms value of the lamp current $I_{fl(rms)}$ by executing the command:

```
xrmsAC_f1(data,col_no_t,col_no_ifl,ki,fo)
```

where *col_no_t* is the time column number, *col_no_ifl* is the lamp current i_{fl} column number, k_i is the current probe conversion factor (as it has been already taken into account on the oscilloscope, the value of 1 should be entered), f_o is the lamp current frequency determined in step 5.1/2(d);

- (f) calculate the peak value of the lamp current $I_{fl(pk)}$ by executing the command:

```
xpkAV(data,col_no_ifl,ki)
```

- (g) calculate the crest factor k_{ci} of the lamp current,

$$k_{ci} = \frac{\Delta I_{pk}}{I_{rms}} \quad (5.1)$$

More calculations in the Scilab software will follow in step 5.4/1.

5. In the SP107 application, open the file containing the lamp voltage waveform u_{fl} recorded in step 4.2/10. Using cursors, determine the peak value of this voltage $u_{fl(pk)}$.
6. Based on results obtained in steps 4, 5 and 5.1/2(d), judge whether the circuit properly fulfills its role as a lamp ballast (see Ref. B [14]) with respect to:
 - (a) limiting the lamp current $I_{fl(rms)}$ to the optimum value according to the rule-of-the-thumb which is Eq. (2) in Ref. B [18] (use the lamp data given in Section 4.1 and take the peak value $u_{fl(pk)}$ as the on-state lamp voltage U_{on});
 - (b) lamp current shape (as described by the crest factor k_{ci}) with respect to lamp life maximization (see Ref. B [14], “The fluorescent lamp”);
 - (c) operation frequency (see Ref. B [14], “Why electronic ballasts?” and following sections).

5.4. The rectifier and electromagnetic compatibility

- * Based on the waveforms of the mains voltage u_i and the current drawn from the mains i_i recorded in steps 4.3/3–4 for two values of the rectifier's filter capacitor C_6 , describe numerically the effect of the input rectifier on the network:

- successively open each of the two files containing the u_i voltage and i_i current waveforms in the SP107 application and save it to a text file, choosing *Data ▶ Save* from the menu and selecting the *Table (*.tab)* format;
- read the first TAB file saved into *header* and *data* matrices by executing the command:

```
[header, data]=wczytaj_sp107('file_name.tab');
```

- display the file's header by typing:

```
header
```

and, by comparison of channel numbers with waveforms visible in SP107 window, determine which column of the *data* matrix contains values of time, which—values of the voltage, and which—those of the current;

- determine the spectrum of the current drawn from the mains and its total harmonic distortion (THD) d_{hi} by executing the command:

```
dhi=widmo_ii_en(data, col_no_t, col_no_ii, ki, pnom)
```

where:

- col_no_t and col_no_ii are the numbers of the columns containing the time and current values, respectively,
- k_i is the current probe conversion factor [see step 5.3/4(e)],
- P_{nom} is the nominal power of the lamp (see Section 4.1);

The above function returns the harmonic distortion coefficient d_{hi} and displays the spectrum (blue bars) along with the (upper) boundary derived from a relevant electromagnetic compatibility standard (red line). Save the spectrum image as an image file (choose *File ▶ Export* from the menu, the PNG format is suggested);

- determine the power factor λ of the circuit and the phase shift φ_1 between the fundamental components of voltage and current by executing the command:

```
[lambda, phi1]=lambda_phi(data, col_no_t, col_no_ui, col_no_ii, ki)
```

where col_no_ui is the number of the column containing the voltage values and other parameters' meanings and values are the same as in sub-step (d);

- repeat the steps (b)–(e) for the second file.

- * In the SP107 application, based on the u_d voltage waveforms recorded in steps 4.2/7 and 4.3/5 for two values of the rectifier's filter capacitor C_6 , read out the peak and valley values. Next, use them to calculate the rectifier output voltage ripple factor r_{uo} in either case.
- * Collect the numerical results obtained in steps 1–2 in a table.
- * Based on the tabulated data, state:
 - how the increase in the capacitance value affected the rectifier's output voltage ripple factor r_{uo} ;
 - how the increase in the capacitance value affected the current harmonics emission and, consequently, meeting the requirements of electromagnetic compatibility standards;

- (c) whether the requirement of low ripple at the output and the one of low harmonic distortion at the input are mutually compatible or exclusive.
5. * Based on the oscilloscope image of the mains voltage u_i determine whether the conditions for the relationship (16.26) from Ref. D are fulfilled (see that section's title). Based on the tabulated data check whether this relationship has indeed been met in the circuit under investigation. Add the power factor values calculated based on this relationship the result table, denoting them as λ .

6. Expected Report Contents

- Block diagram of the investigated circuit with waveform parameters labelled in key points, oscilloscope images that have been used to determine these parameters, and result analysis, according to Section 5.1
- Peak values of transistor voltage and current and oscilloscope images that have been used to determine them, according to step 5.2/1–2 (i.e., $u_{CE,T2(pk)}$ and $i_{C,T1(pk)}$ values)
- Voltage and current rated values read out from the data sheet of the investigated transistor, compared to the determined working values, according to step 5.2/3(a)–(b)
- Safe operating area diagram for the investigated transistor with extreme operating points marked together with an analysis, according to step 5.2/3(c) (i.e., the diagram from the data sheet with the on-state and the off-state operating points marked)
- An approximate value of the current gain for the investigated transistor at the recorded peak collector current value and the required base current calculated on this basis, according to step 5.2/3(d)
- Symbols, prices and parameters of found transistors of different types with an analysis with respect to BJT applications, as well as a printed copy or screen shot of web pages containing source data, according to step 5.2/4 (i.e., data for 1 BJT, 1 MOSFET and 1 IGBT with parameters suitable for application in the investigated circuit)
- Fluorescent lamp voltage and current values and oscilloscope images used to obtain them, as well as the calculated lamp current crest factor value, according to steps 5.3/4–5 (i.e., the values of $I_{fl(rms)}$, $I_{fl(pk)}$, k_{cib} , $u_{fl(pk)}$)
- Quality analysis of the investigated circuit as a lamp ballast, according to step 5.3/6
- * Result table according to steps 5.4/3 and 5, input current spectrum plots obtained in step 5.4/1 and oscilloscope images used to obtain these results, labelled with filter capacitor values (i.e., C_6 , d_{hi} , λ , φ_1 , λ' values and oscilloscope images for two values of the C_6 capacitor)

- * Analysis of the effect of the C_6 capacitor on circuit operation, according to step 5.4/4
- * Calculations proving that the relationship linking the power factor and the harmonic distortion coefficient at sinusoidal voltage has been fulfilled (or not), according to step 5.4/5

7. Required Knowledge

7.1. Prerequisites

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

7.2. 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 in characteristic points of the circuit, drawbacks of the standard ballast and advantages of the electronic ones. (see Ref. B, report)
3. Voltage-fed half-bridge inverter: simplified electrical schematic; active leg middle point voltage, output (lamp) current, semiconductor switch current waveforms. (see Ref. B, 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. C)

8. 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.