



POWER DEVICES AND SYSTEMS LABORATORY

Exercise 4^A

Insulated Gate Bipolar Transistor Full-Bridge Converter Electric Motor Control

Indicatory work plan

15'	30'	45'	1 ^h	1 ^h 15'	1 ^h 30'	After Class
3.2/1-10	3.2/11-19	3.3/1-4		3.3/5-6	3.3/7-12	4

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Exercise Introduction

1. Exercise Aim and Plan

The aim of this exercise is first to get acquainted with yet another work configuration of power semiconductor devices, the bridge. Second, electric motor control will be taken advantage of as a practical application example.

Generally speaking, both these issues are fairly complex due to the large number of possible control strategies for bridge switches as well as the multitude of motor solutions. For this reason, we will restrict to a control method that is simple and yet enables a complete analysis of the circuit. Also the motor chosen—a permanent magnet DC one—is among all the electric motors the easiest one to control. It will enable gaining the most basic knowledge about the specificity of power converter operation with RLE receivers. A DC/DC bridge converter will be the power converter used in this exercise.

Converter characteristics will be determined in this exercise, including those independent and those dependent on the receiver, as well as one of the typical characteristics of the electric motor. On the other hand, the operation of the DC/DC bridge converter will be investigated at the current and voltage level, including drive circuits of the transistor switches.

2. Insulated Gate Bipolar Transistor

2.1. Recommended reading

Ref.	Textbook	Excerpt	Equivalent in the Polish Manual	Complementary Reading	Complements in this Manual
A	Bal	8, 8.1, 8.2, 8.2.1, 8.2.2, 8.3, 8.3.1, 8.3.2	2.1, 2.2		
B	Bal	8.6, 8.6.1	2.3.c, 2.5	[21] 8.5 Switching Times, Switching Energy	
C	Bal	8.2.2, 8.3.2, 8.6.2.3, 8.7	2.4		

3. Measurements

3.1. Test circuit

The schematic diagram of the laboratory circuit is presented in Fig. 1. The circuit allows measurement of terminal voltages and collector current of the transistor under investigation which is IRG4BC20S.

Element values are as follows:

- load resistance: $R_1 = 4,7 \Omega$,
- gate resistance: $R_G = 10 \Omega; 150 \Omega; 300 \Omega; 600 \Omega$.

The purpose of the switches found on the panel is as follows:

- K_1 enables selecting the circuit configuration (0/L/H/P), the 'L' being the only one used in this exercise,
- K_2 enables selecting the load configuration (R/RL/RLD), the resistive one with the R_1 resistor being the only one used in this exercise,
- K_5 enables changing the gate resistance R_G by connecting an appropriate resistor.

In order to eliminate the influence of self-heating on the transistor under test as well as to allow measurement of significant currents without the risk of thermally damaging the transistor, the measurements are conducted using single switching pulses (turning the transistor on and back off after a short period of time). A rectangular pulse of the u_g voltage is generated each time the green button located on the front panel is pressed (switch K_4 in Fig. 1); the pulse width t_p is of several dozen microseconds and its amplitude is approximately equal to the control (drive) circuit supply voltage U_{GG} . This voltage, equal to 15 V, is generated internally with a built-in power supply supplied from the 230 V mains.

Taking the above into consideration, it is required to generate a switching pulse every time settings have changed. This also applies to situations where changes are only made in the measurement equipment (oscilloscope, current probe). Only after a new pulse is generated will the oscilloscope capture waveforms using the new settings and the changes will have their effect. Until then, waveforms will not change, even though they may appear to do so (i.e. horizontal waveform

magnification by changing the time base). The oscilloscope memory will still contain the old data and the plot points will just be stretched along the time axis. This mechanism resembles digital zoom—it does not allow to capture a more precise image but only stretches it. The oscilloscope used in the laboratory indicates this by greying out waveforms. The above also applies to vertical magnification of the plots (i.e. changing the voltage gain of the oscilloscope or the conversion factor of the current probe).

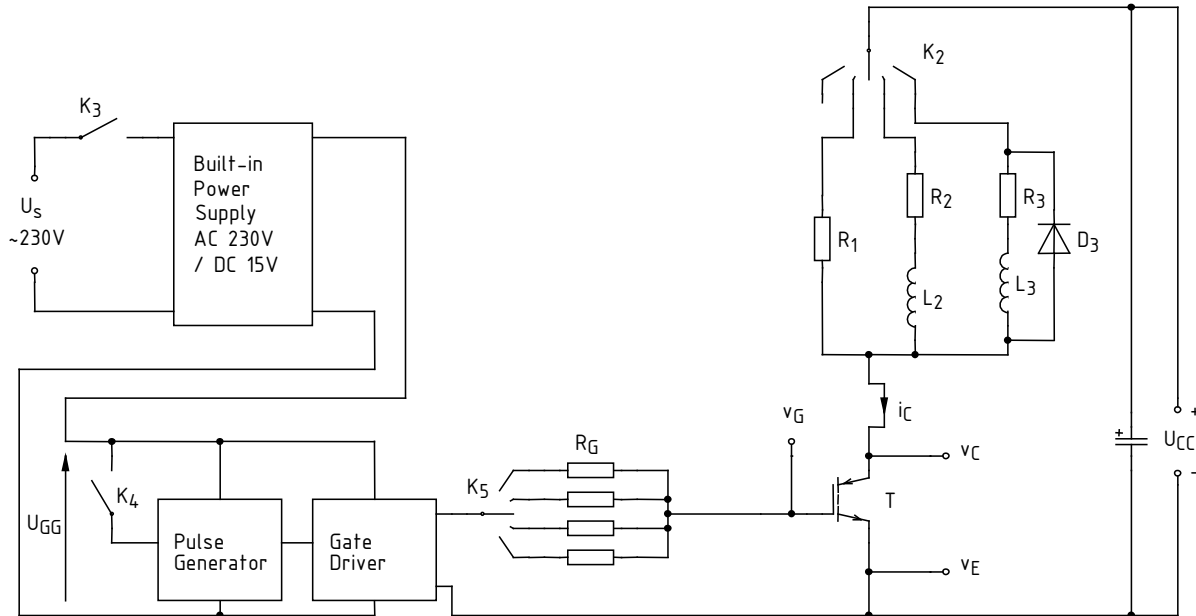


Fig. 1. Schematic diagram of the test circuit for investigation of dynamic properties of a standard IGBT (for the K_1 switch set in the L, low-side switch, position)

Voltage measurements are performed using voltage probes appropriately connected to the banana sockets found on the circuit's panel, labelled v_E , v_G and v_C . For this purpose, banana connectors are provided that enable attaching a probe.

Collector current measurement is performed by clamping a current probe around the wire led out above the panel, labelled i_C (whose location within the circuit is marked with an arrow in Fig. 1). The arrow on the current probe body indicates the positive reference direction. The clamping should be done in such a way that the probe reference direction agrees with the one in the schematic diagram.

For recording data from the oscilloscope, the WaveStar for Oscilloscopes application should be used which is accessible through the Start Menu, *Pomiary* tab, in a way described later in this manual.

3.2. Preparation for measurements

Measurement set-up configuration

In order to save time, execute next steps concurrently with step 1.

1. Turn on the computer. After log-on is completed, turn on the oscilloscope and configure the connection to the computer, strictly following the additional instructions available at the laboratory stand. (If the team has already used the TDS224 oscilloscope before, its configuration should not be necessary now unless communication problems occur.)
2. Make sure that the built-in 15 V power supply is turned off (the K_3 switch set to OFF). Plug the power connector in.
3. Set up internal connections of the laboratory circuit:
 - choose the low-side switch topology by setting the K_1 switch to L,
 - choose the resistive receiver R_1 by setting the K_2 switch to R,
 - plug the *PB* wire into the *GND.LHP* socket.
4. Use a power supply with two adjustable sections to power the circuit. Before connecting, make sure that it is switched off. Connect the outputs of one of the adjustable sections to the U_{CC} (not *V ZAS H*) on the circuit's panel.
5. Switch the power supply into the independent operation mode (two buttons in the middle of the front panel). Turn all the knobs down to zero (extreme counterclockwise position).
6. Attach 10:1 attenuation voltage probes to the circuit so that to measure the transistor's gate-emitter voltage u_{GE} in channel 1 and its collector-emitter voltage u_{CE} in channel 2.

Warning!

1. The ground leads (alligator clips) of the voltage probes are mutually shorted inside the oscilloscope and connected to the protective earth of the mains; both of them must therefore be always connected to the same potential. Any other configuration may cause a significant current to flow through the oscilloscope and damage its input circuitry.

2. Do not touch the elements at which the power circuit supply voltage is present (especially the v_C potential connector) during measurements.

3. Before proceeding, connections must be checked by the teacher.

7. Turn on the built-in 15 V power supply with the K_3 switch. The green LED indicator should turn on.

Before proceeding, read the next step instructions entirely together with additional remarks!

8. Turn on the external power supply. Slightly increase the current limiter threshold (*Current* knob) of the section supplying the power circuit until the red LED indicator (*C.C.*) turns off. Set the voltage (*Voltage* knob) to 60 V. A green LED indicator on the circuit's panel should turn on.

When the circuit operates correctly, the only current indicated by the power supply's ammeter should be a constant LED indicator current (approx. 0,01 A) and a possible transient current charging the blocking capacitor inside the circuit (not more than 0,05A). If anything else is observed during adjustment or later, turn off the power supply immediately and ask the teacher to check the circuit once again.

9. Increase the current limiter threshold of the section supplying the power circuit to the maximum (extreme clockwise knob position).
10. Using the *CH1/2/3/4* buttons on the oscilloscope, display the waveform from channel 1 and hide waveforms from all the other channels.

Pressing the *MENU* button of a given channel toggles between displaying and hiding the corresponding waveform. When a given waveform is displayed, this is indicated by an arrow pointing at zero level left of the graticule and by a “CHx” symbol below the graticule.

Test measurement

11. Use the K_5 switch to select the $600\ \Omega$ gate resistor.
12. Configure the oscilloscope:
 - (a) channel 1 (*CH1 MENU* button):
 - Coupling: DC,
 - Probe: 10x,
 - Invert: Off,
 - gain adequate to the expected amplitude of the u_{GE} voltage (*CH1 VOLTS/DIV* knob; the current setting is displayed next to the channel symbol CH1);
 - (b) time base:
 - trigger moment approximately in the middle of the screen (*HORIZONTAL POSITION* knob; current setting is indicated by the arrow above the graticule),
 - time base appropriate for the expected duration of the driving pulse width (*SEC/DIV* knob; current setting is displayed under the graticule next to the M symbol);
 - (c) triggering (*TRIGGER MENU* button):
 - edge trigger,
 - trigger on the rising slope,
 - the u_{GE} waveform as the triggering source (appropriate channel number in the *Source* field),
 - normal mode,
 - coupling with noise rejection,
 - trigger level at approximately half the expected range of the u_{GE} voltage (*TRIGGER LEVEL* knob; current setting is displayed under the division line next to the *CH1* trigger channel symbol and the edge symbol \lrcorner).
13. Press the green K_4 button in order to generate a transistor switching pulse. A “Trig’d” message should appear briefly on the oscilloscope screen above the graticule and the u_{GE} voltage waveform should be displayed. If this does not happen, check the oscilloscope settings (especially the channel 1 amplification *Volts/Div*, the time base *Sec/Div* and the trigger level *Level*). If this does not help, ask the teacher to check the settings.
14. Adjust (generating the switching pulse after each change of settings) the time base and trigger moment position (*SEC/DIV* and *HORIZONTAL POSITION* knobs) so that the pulse of the u_{GE} voltage is visible in its entirety (see Fig. 2) and occupies most of the screen horizontally.
15. Display the channel 2 waveform, which is the u_{CE} voltage, using the *CH2 MENU* button. Check:
 - whether channel settings agree with those given in step 12(a), modifying them if necessary,
 - whether the waveform does not go beyond the screen (ignore possible short spikes) or whether its amplitude is not too low (not clearly visible), adjusting the gain and the zero level if necessary (*VOLTS/DIV* and *VERTICAL POSITION* knobs),
 - whether the waveform is correct (see Fig. 2).
16. Following the additional manual available and the laboratory stand, configure the current probe amplifier and its connection to the oscilloscope. Read and apply obligatorily all the guidelines given in that manual pertinent to oscilloscope configuration.

At the proper time:

 - attach the amplifier’s output to channel 4;

- adjust the current/voltage conversion factor so that it is possible to measure and display a waveform of the expected amplitude on the oscilloscope (see information about probe amplifier operation and its coupling with the oscilloscope given in the probe manual; calculate the amplitude using the known parameters of the receiver and power supply assuming that the main terminals of the transistor are perfectly shorted).

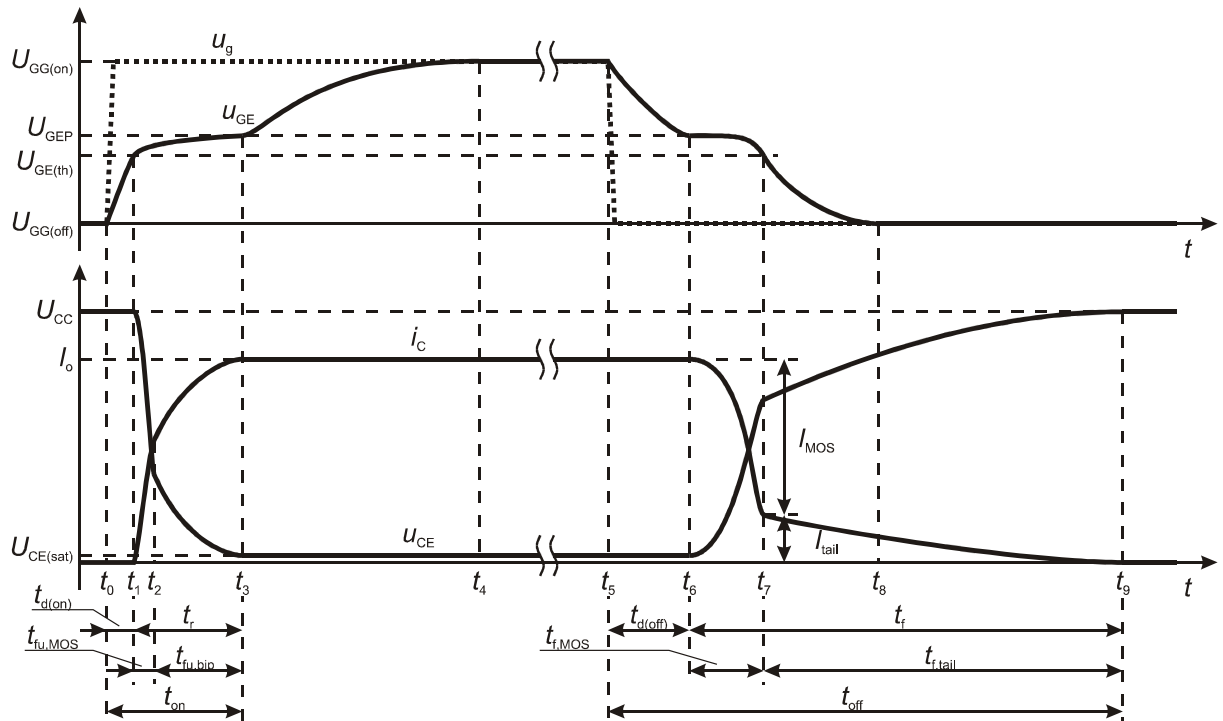


Fig. 2. The waveforms of u_{GE} , u_{CE} and i_C during one switching cycle of an IGBT with resistive load

17. Apart from the adjustments indicated in the current probe instructions, set:
 - (a) on the probe amplifier, DC coupling;
 - (b) on the oscilloscope (*CH4 MENU*):
 - DC coupling,
 - invert de-activated (off).
18. Clamp the current probe around the appropriate wire so that to measure the collector current i_C and so that the measured current direction agrees with the real one.
19. Generating the switching pulse, adjust:
 - amplification along the measurement path as described in the manual: [A6302/A6312+AM503B] on the probe amplifier, not the oscilloscope, [TCP312+TCPA300] at channel 4 of the oscilloscope, not the probe amplifier, unless the amplification setting on the amplifier is incorrect (which may be reflected in a current waveform far from a rectangular pulse, among others),
 - waveform position using the channel 4 *VERTICAL POSITION* knob (on the oscilloscope), so that the current waveform is displayed optimally, i.e. maximally fills the screen vertically but does not go beyond the screen. Check that the waveform is correct (see Fig. 2).

If the the current/voltage conversion factor of the probe amplifier has been significantly changed (by an order of magnitude or more), repeat the calibration and de-gauss procedure after closing the probe without any wire inside.

3.3. Measurement procedure

Full switching cycle

1. Generate a switching pulse. Make sure that the image of the waveforms is still correct. Check if the current pulse amplitude as seen on the oscilloscope is approximately equal to the one calculated in step 3.2/16 (see the guideline concerning reading out the voltage/current conversion factor in the current probe manual).

Skipping the above step may cause result processing to become impossible!

Although the current consumption period is short, it significantly exceeds the output current capability of the power supply. Due to this fact, sometimes the current limiter may be activated, limiting both current and voltage. Because of that, after generating a switching pulse make sure that the on-state i_C current value and off-state u_{CE} voltage value (equal to the power supply voltage U_{CC}) observed on the oscilloscope are correct. Otherwise, generate a switching pulse again.

2. Adjust, if necessary:
 - the gain of the voltage measurement channels (1 and 2) using the *VOLTS/DIV* knob,
 - the amplification along the current measurement path as described in the current probe manual:
 - [A6302/A6312+AM503B] on the probe amplifier, not the oscilloscope,
 - [TCP312+TCPA300] at channel 4 of the oscilloscope, not the probe amplifier,
 - waveform position using the *VERTICAL POSITION* knobs,

so that each waveform, from its zero level (indicated by an arrow left of the graticule) to its peak value maximally fills the entire screen area vertically but does not go beyond the screen (still ignoring possible short spikes).

3. [A6302/A6312+AM503B] The current probe used passes the DC component of waveforms incorrectly, which may cause improper indication of the zero level of the current. As a result:
 - ensure that the collector current displayed on the oscilloscope is found at the zero level (marked with an arrow with channel number) within the interval where the transistor is off (zero drive voltage u_{GE});
 - if it is not found at this level, manually shift the waveform vertically as appropriate, using the *Output DC Level* knob on the current probe amplifier (not the *Vertical Position* knob on the oscilloscope);
 - if needed, correct the position of the current waveform on the oscilloscope's screen using the appropriate *Vertical Position* knob on the oscilloscope.

Waveform correctness from the above point of view should be checked each time before waveforms are downloaded from the oscilloscope.

4. Save the set of the three waveforms (u_{GE} , u_{CE} and i_C , together):
 - (a) in the WaveStar application, create a new sheet of the *YT Sheet* type;
 - (b) from the side panel (*Local* ▶ oscilloscope name ▶ *Data* ▶ *Waveforms* ▶ channel symbol), drag the three waveforms displayed on the oscilloscope to the new sheet;

After waveforms have been dragged once, it is sufficient to just refresh them later by pressing the *Refresh Sheet* button or selecting the *View, Refresh Datasheet* from the menu.

A plot can be removed from a sheet by clicking its number left to the graticule and pressing the Delete key.

- (c) save the sheet containing all the three plots in the WaveStar application format (SHT) using the *Save Datasheet* button (Ctrl+S);

Don't use the *Save Worksheet* function which does not save any measurement data, just the names of the sheets being currently open.

- (d) write down the current probe amplification setting (see the current probe manual; a *Notes Sheet* may be used for this purpose).

Detailed switching observation

5. Record waveforms enabling determining time and energy-related dynamic parameters describing transistor's turn-on (not any other operating state):
- (a) adjust the time base (*SEC/DIV*), trigger moment position (*HORIZONTAL POSITION*) and possibly the trigger level (*LEVEL*) so as to observe the turn-on (not any other operating state) of the transistor with as much accuracy as possible, considering phenomena in the transistor's main circuit, i.e. the t_{on} time interval (see Fig. 2);

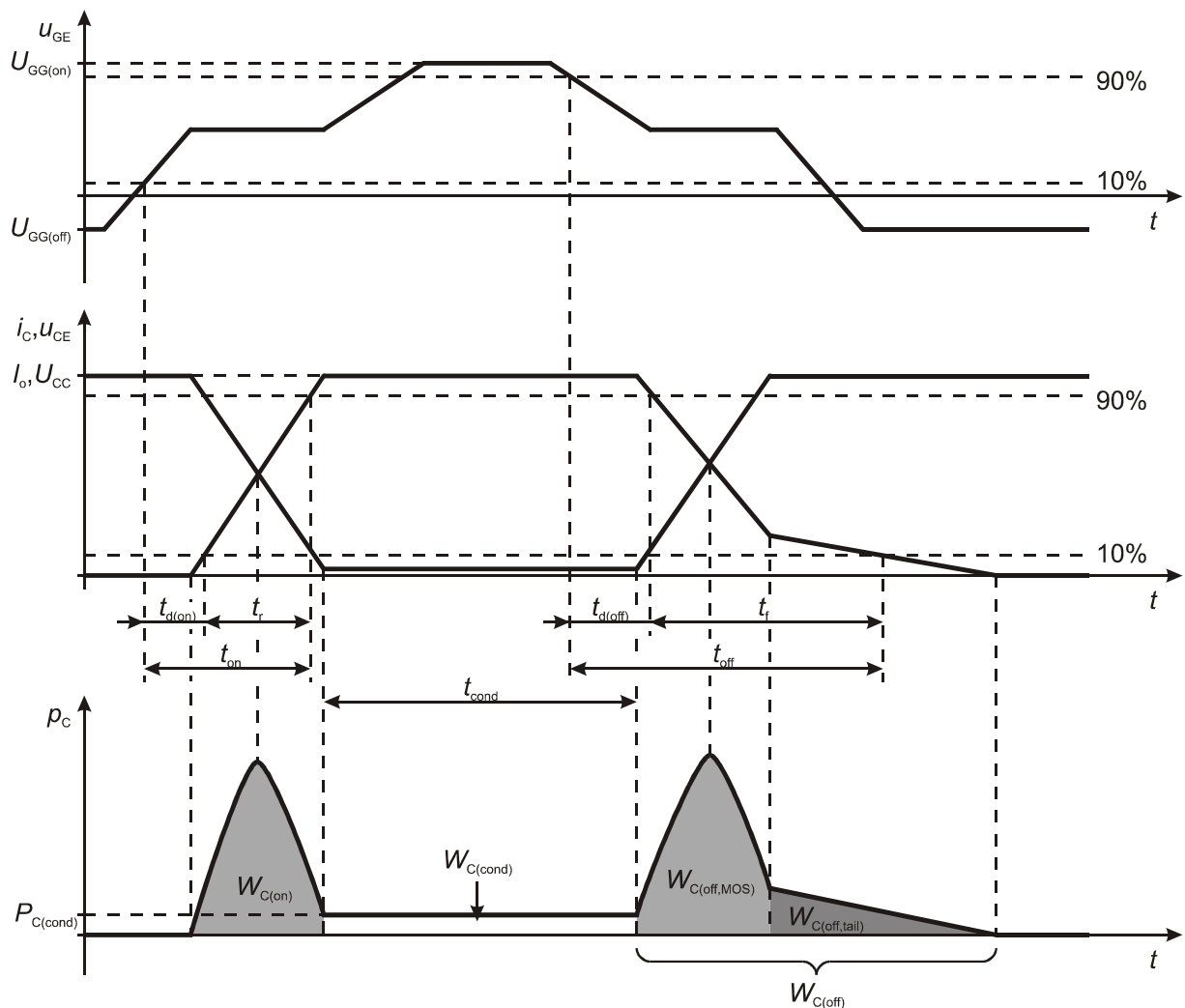


Fig. 3. The most important IGBT dynamic parameters (the plots do not reproduce the exact waveforms)

- (b) make sure that all the threshold crossing moments are visible on the screen enabling determining the time-related parameters for turn-on (see Fig. 3);
- (c) make sure that channel settings still meet the requirements of given in step 2, however, taking possible overvoltages into consideration now;
- (d) [A6302/A6312+AM503B] check and (if needed) modify the current measurement path settings according to step 3;
- (e) in the WaveStar application, create two new sheets one *YT sheet* and one *Power Harmonics*;

The *Power Harmonics* sheet allows, among others, multiplying two waveforms. If these two waveforms are a current i flowing between two circuit nodes and the voltage u between these nodes, then the obtained $i \cdot u$ product will by definition be the instantaneous power p dissipated in the components located between these two nodes.

- (f) use the *Power Harmonics* sheet to calculate the instantaneous power loss p_C waveform:
- drag the i_C current waveform from the side panel to the *Current Waveform* window at the bottom of the *Power Harmonics* sheet;
 - drag the voltage waveform appropriate for obtaining the power loss in the transistor's collector circuit p_C (not any other waveform product) to the *Voltage Waveform* window;
- (g) drag all the four waveforms, u_{GE} , u_{CE} , i_C and p_C , to the *YT Sheet*;

In order not to waste time downloading the waveforms again from the oscilloscope (this action will be repeated several times), all the three waveforms already displayed in the *Power Harmonics* sheet should be dragged from that sheet and not from the side panel. Only the missing waveform can be dragged from the side panel.

Do not change any settings in the WaveStar application until all measurements described in this manual are finished. The only exceptions are:

- changing the colour from the toolbar at the top of the sheet's window;
- moving the zero level using the arrow left of the graticule;
- moving the trigger moment position as described in sub-step (h).

All other changes will cancel the possibility of refreshing the sheets, which will significantly increase the amount of time needed to complete the exercise.

- (h) it is usually necessary to synchronise the power waveform with the others; to achieve this, select the power waveform by clicking its number left of the graticule, then move the coloured slider above the graticule, positioning it exactly between the white markers in the shape of square brackets;
- (i) Save the *YT Sheet* containing the complete set of four waveforms and write down the current probe amplification setting (if it has changed).
6. Change the gate resistance to 300 Ω and repeat step 5, however, instead of creating new sheets and dragging the waveforms [sub-steps (e)–(g)], just do the following:
- first, instead of sub-step (f), refresh the *Power Harmonics* sheet (*Refresh Sheet* button or *View, Refresh Datasheet* from the menu),
 - next, instead of sub-step (g), refresh the *YT Sheet*.
7. * Repeat step 6 for $R_G = 150 \Omega$.
8. Record waveforms enabling determining time and energy-related dynamic parameters describing transistor's turn-off:
- (a) switch to falling-edge u_{GE} waveform triggering (*TRIGGER MENU, Slope*);
- (b) repeat step 5, but:
- instead of transistor's turn-on, its turn-off during the t_{off} time interval should obviously be considered as defined based on physical phenomena (i.e., not according to technical definitions but according to Fig. 2);

The above sub-step does not tell to observe *any fragment* of the t_{off} time interval, but *the t_{off} time interval*, meaning this entire time interval. Incorrect execution of this sub-step will make it impossible to obtain results required and measurements will have to be repeated. In case of doubts, study the abovementioned figure once again considering all the three waveforms displayed on the oscilloscope and consult your result with the teacher.

- pay special attention to performing sub-step 5(d) (if the relevant probe and amplifier are used);

Due to the current tail occurring, the collector current should be found at the zero level only after the tail ends and not when the drive voltage u_{GE} falls down to zero (see Fig. 2). In case of doubt, consult the oscilloscope image with the teacher.

- instead of creating new sheets and dragging the waveform [steps (e)–(g)], just first refresh the *Power Harmonics* sheet and then, the *YT Sheet*.
9. Repeat step 8 for $R_G = 600 \Omega$.
 10. * Repeat step 9 for $R_G = 150 \Omega$.

Measurement termination

11. [A6302/A6312+AM503B] On the current probe amplifier, bring the *Output DC Level* knob setting to the value of 0.0 (the setting is displayed in the *Current/Division* field during adjustment).
12. Decrease the supply voltage of the external power circuit to zero. Wait until the green LED on the circuit's panel goes out. Turn off the power supply.
13. Switch the built-in 15 V power supply off and unplug it from the mains.

4. Result Elaboration and Analysis

4.1. Stationary state parameters

1. Start the WaveStar application.
2. Open the waveform set $\{u_{GE}; u_{CE}; i_C\}$ for the full driving voltage pulse, registered in step 3.3/3.
3. Based on of the current probe's current/voltage conversion factor written down, calculate the coefficient k_i in amps per volt, which will be used to multiply a value shown in WaveStar in volts in order to obtain a corresponding real current value in amps.

Values shown in WaveStar for current waveforms are indeed voltage values that came from the current probe amplifier and were registered by the oscilloscope. We will denote this with an asterisk. Such a voltage is proportional to the current according to the current probe conversion factor written down. The coefficient, resulting directly from this factor, but expressed in SI units, i.e. A/V, for practical reasons, will allow obtaining real values in amps. (According to the A6302/A6312+AM503B current probe and amplifier manual, the value indicated on the display was expressed in A/10 mV or in mA/10 mV.) If, for example, the current probe conversion factor has been 5 A / 10 mV, then $k_i = 5 \text{ A} / 10 \text{ mV} = 500 \text{ A/V}$. The real value of current in amps is $i [\text{A}] = k_i [\text{A/V}] \cdot i^* [\text{V}]$.

4. Verify the correctness of the current value conversion:
 - (a) using a horizontal cursor, read out the drain current value $I_{C(\text{on})}^*$ (in volts);

Slight overshoots that sometimes may be seen in the current waveform (upwards after turn-on, downwards after turn-off), result only from the limited frequency bandwidth of the current probe. They should be therefore neglected during analysis. If there is an overshoot with considerable amplitude, it should be assumed that the high level of the current pulse is indeed a horizontal line at the level that the waveform attains after the visibly faster growth in the beginning of the pulse.

Remarks on the use of cursors in the WaveStar software:

1. In order to activate cursors, chose *View* ▶ *Properties* ▶ *Cursor* from the menu and select a cursor type appropriate for the measurement. In the active *YT Sheet*, values related to the active waveform will appear, depending on the cursor type selected:

- X, Y – the coordinates of the active cursor (continuous line);
 - X1, Y1 and X2, Y2 – the coordinates of the first and the second cursors;
 - dX, dY – the differences of the two cursors' coordinates.
2. A waveform can be activated by clicking its number shown left of the graticule. The number of the active waveform is constantly highlighted.
 3. After switching to another waveform, a horizontal cursor remains on the same level in volts (not in divisions). This means that when a large difference in vertical scales (V/div) is present between the two waveforms, the cursor can be placed beyond the display. In such a situation, temporarily increase the V/div coefficient, then move the cursor to a level close to zero and after that restore the previous coefficient value.
 4. Distinguishing different waveforms will be easier when coloured legend is chosen: in the menu *View ▶ Properties ▶ Plot*, select *Waveform notes color match waveform color*.
- (b) using the coefficient k_i determined in step 3, calculate the real drain current value (in amps) $I_{C(on)}$;
 - (c) check if the $I_{C(on)}$ value determined conforms with test circuit data and settings [see Section 3.1 and step 3.2/16]; if not, identify the source of this discrepancy (e.g. an improper gain setting on channel 4 of the oscilloscope different from 10 mV/div in the case of the A6302/A6312+AM503B current probe and amplifier, a mistakenly noted current probe amplifier indication, wrong load resistor network configuration) because the k_i coefficient is very important for calculations that follow.
5. Based on the oscilloscope image, determine the voltage and current thresholds necessary for using the technical definitions of the time-related dynamic parameters (see Fig. 3 and Ref. 21, Section 8.5):
 - (a) using a horizontal cursor, read out the on-state gate-emitter voltage value $U_{GE(on)}$;
 - (b) calculate the threshold values used in the technical definitions of the time-related dynamic parameters (for current also in volts as it will be easier to read values out of oscilloscope images).

4.2. Turn-on and turn-off parameters

Starting Scilab

1. Run the numerical computation package Scilab.
2. Load the script that contains functions necessary for dissipated energy calculation by executing the command:

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

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

3. In order not to have to enter the full path for all the processed files (WaveStar output files), the working directory may be changed to the directory that contains them by executing the command:

```
cd('measurement_path');
```

Time-related parameters

4. In WaveStar, open the waveform set $\{u_{GE}; u_{CE}; i_C; p_C\}$ for the turn-on process, for $R_G = 600 \Omega$, registered in step 3.3/5.
5. In the WaveStar software determine the time-related dynamic parameters for turn-on:
 - (a) using paired cursors, read out the turn-on delay time $t_{d(on)}$ according to its technical definition, using the thresholds calculated in step 4.1/5 (see Fig. 4);

Exemplary readings presented on the figures in this sub-section show only the way how the parameters should be measured. They do not suggest any correct values, and the way that waveforms should look like in the sheet. In order to get exemplary results more readable, oscilloscope images contain only waveforms necessary to understand particular section.

- (b) using paired cursors, read out the rising time t_r according to its technical definition.

Energy-related parameters

6. Based on the current probe current/voltage conversion factor written down, determine the k_i coefficient for the oscilloscope image currently processed (if the amplification setting was not changed, this is not necessary as the value calculated in step 4.1/3 remains valid).
7. In WaveStar, determine the parameters of the power pulse generated during turn-on:
 - (a) using cursors, read out the coordinates of the time moments $t_{inf(on)}$ and $t_{sup(on)}$ that correspond to the beginning and the end of the power pulse;

For simplicity, disregard the voltage and current thresholds. Base mainly on the instantaneous power waveform p_C assuming that it is sufficient to distinguish dynamic states from static ones (see Fig. 5). Refer to the u_{GE} voltage waveform as well in case of doubt (especially to determine the turn-on end and the turn-off beginning).

- (b) export the data to a CSV (*comma-separated values*) text file from the menu *File* ► *Export Datasheet* ► *CSV*.
8. In Scilab, calculate the energy dissipated during turn-on $W_{C(on)}$:
 - (a) read in the data exported by executing the command

```
[header, data]=wczytaj_ws('file_name.csv');
```

During calculations for subsequent cases, a previously executed command can be recalled by pressing the up-arrow on the keyboard.

- (b) calculate the energy $W_{C(\text{on})}$ as the integral of p_C for the interval from $t_{\text{inf}(\text{on})}$ to $t_{\text{sup}(\text{on})}$, taking the k_i coefficient into account, by executing the command:

```
calka_infsup(data, pc_waveform_no, tinf, tsup, pd0, ki)
```

The parameter $pc_waveform_no$ is the number of the p_D waveform according to the increasing numbering in WaveStar software (not the channel number on the oscilloscope). If, for example, waveforms displayed in WaveStar are: 2) u_{CE} , 3) i_C , 4) p_C , 6) u_{GE} , then the p_C waveform is the third consecutive, so $pc_waveform_no = 3$ should be entered; if numbering starts from 1 and there is no gap, then $pc_waveform_no$ is identical to the one shown in WaveStar.

The parameter $pc0$ allows taking into account the zero level shift of the p_C waveform (non-zero value in the off-state) caused by imperfection of the current probe. If this shift is considerable, then the false (non-zero) value of p_C indicated in WaveStar in the off-state should be entered (in V·V without converting to watts, see Fig. 6, lower cursor position). If the shift is small as compared to the power pulse amplitude, enter 0.

An alternative version of the integral function can be used, $calka_infdelta()$. It works in a way identical to the previous one except that instead of $tsup$, the parameter $deltat = t_{\text{sup}(\text{on})} - t_{\text{inf}(\text{on})}$ should be entered. It may be more convenient because both readings (X and dX) can be copied from the *YT Sheet* at the same time.

An example, assuming that the sequence of waveform presentation in WaveStar has been as follows: 1) u_{CE} , 2) i_C , 3) u_{GE} , 4) p_C , and that other parameters have had values as in the exemplary figures 5 and 6 (see figure labels):

```
calka_infsup(dane, 4, 0.02E-6, 1.26E-6, -64.4E-3, 200)
```

or

```
calka_infdelta(dane, 4, 0.02E-6, 1.24E-6, -64.4E-3, 200)
```

- (c) the above function returns the value of the integral in joules and, for verification purposes, plots the p_C waveform shifted by p_{C0} and scaled by k_i as well as fills the area that corresponds to the calculated integral;

based on this plot check, verify whether the integral has been calculated for a proper interval along the power waveform, i.e. for a pulse that can be clearly distinguished from the off-state that precedes it and from the turn-on state that follows, and that the pulse base level is found at the real zero level, i.e. the constant value of the waveform in the off-state, and if not, calculate the energy again;

- (d) save the plot check selecting *File* ► *Export* from the menu (GIF or EMF format should be used).

Further cases

9. Repeat steps 4–8 for the $R_G = 300 \Omega$ (* and $R_G = 150 \Omega$) case, based on the waveforms recorded in step 3.3/6 (* and 3.3/7).
10. Repeat steps 4–8 for the turn-off state, for $R_G = 600 \Omega$, 300Ω (* and 150Ω) so as to determine the time-related dynamic parameters $t_{d(\text{off})}$ and t_f and the energy-related one $W_{C(\text{off})}$, based on the waveform sets recorded in steps 3.3/9, 8 (* and 10).
11. * Repeat steps 4–8 for the IRG4BC20U transistor ($R_G = 600 \Omega$) for both turn-on and turn-off states so as to determine the time-related parameters $t_{d(\text{on})}$, t_r , $t_{d(\text{off})}$, t_f and the energy-related ones $W_{C(\text{on})}$, $W_{C(\text{off})}$.

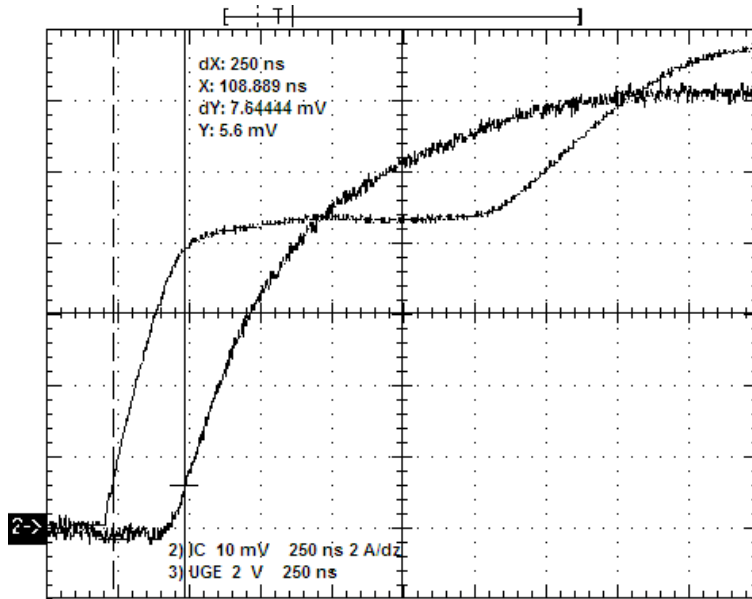


Fig. 4. Exemplary read-out of the $t_{d(on)} = 250$ ns time (dX indication). The Y value shows that the right cursor has been positioned just after the i_C waveform crosses the 10% I_C^* level which has been 58.7 mV in this case.

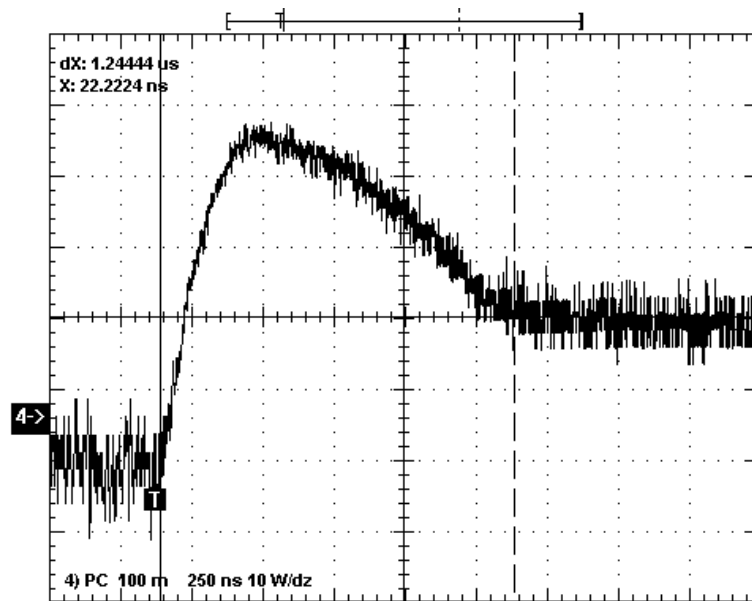


Fig. 5. Exemplary read-out of $t_{inf(on)} = 0.02$ μ s (left cursors, X indication) and $t_{sup(on)} = 1.26$ μ s ($\Delta t = 1.24$ μ s, dX indication) times

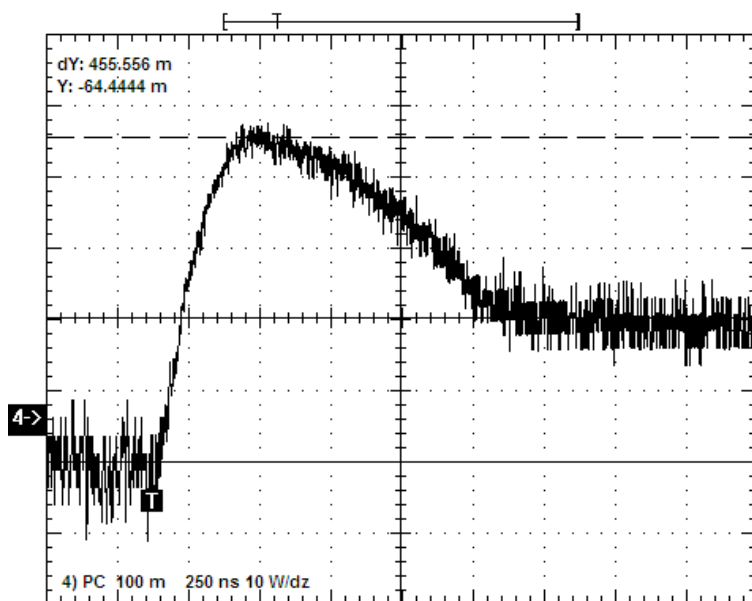


Fig. 6. Exemplary read-out of zero-level offset (indicated by “4->” improperly) of the instantaneous power waveform $\Delta p_C^* = -64.4 \text{ mV}\cdot\text{V}$ (Y indication). It is considerable in this case as it amounts to more than 10% of the power pulse amplitude which is 456 $\text{mV}\cdot\text{V}$ (dY indication)

4.3. Current tail parameters

1. Based on the oscilloscope image for turn-off, for $R_G = 600 \Omega$, determine the current tail parameters:
 - (a) use cursors to determine the current tail amplitude I_{tail} (see Fig. 2);
 - (b) use cursors to determine the approximate current tail duration $t_{f,\text{tail}}$ assuming the criterion of falling to about 5% of its initial value I_{tail} for determining its end (see Fig. 2);
 - (c) use a cursor to determine the time coordinate of the beginning of the current tail $t_{\text{inf(tail)}}$ (the beginning of the $t_{f,\text{tail}}$ interval, the t_7 moment in Fig. 2);
 - (d) following the same procedure as for the $W_{C(\text{off})}$ energy, calculate in Scilab the energy component $W_{C(\text{off},\text{MOS})}$ related to the turn-off of the MOS component of the transistor (see Fig. 3) as an integral over the time interval from $t_{\text{inf(off)}}$ (which value has been determined in step 4.2/10) to $t_{\text{inf(tail)}}$; save the plot check;
 - (e) Calculate the $W_{C(\text{off,tail})}$ energy component as the difference between the total energy $W_{C(\text{off})}$ and the $W_{C(\text{off},\text{MOS})}$ energy.
2. Obtain plots that will enable comparing current tails for different operating conditions:

Numerical comparison of current tail parameters is difficult because of the high measurement uncertainty (see Ref. 21). We will therefore rely on graphical analysis partly.

- (a) from the *YT Sheet* for turn-off at $R_G = 600 \Omega$, remove all the waveforms except the i_C current one;
- (b) making use of the possibility to move waveforms between sheets, add the i_C current waveform from the *YT Sheet* containing results for turn-off at $R_G = 300 \Omega$ (* and at 150Ω);
- (c) if time scales (as indicated in the legend) of different waveforms differ, make them the same using the pull-down list found in the toolbar in the *YT Sheet* window, or selecting *View > Properties* from the menu, switching to the appropriate waveform tab and setting *Horizontal Scale*;
- (d) synchronise the waveforms with respect to the beginning moment of the current tail using the slider above the graticule (i.e. move waveforms horizontally so as all the current tails originate from the same moment);
- (e) set zero levels (i.e. current levels in the off-state) of all the waveforms at the same level dragging their numbers left to the graticule, or selecting *View > Properties* from the menu, switching to the appropriate waveform tab and setting *Vertical Position*;
- (f) save the obtained sheet under a new file name.

4.4. Result recapitulation

1. Gather the results obtained in Section 4.2 in a table (or possibly two tables, for turn-on and turn-off separately) containing the following parameters for both (* all three) R_G cases:
 - R_G ;
 - $t_{d(\text{on})}$, t_r , $W_{C(\text{on})}$ for turn-on;
 - $t_{d(\text{off})}$, t_f , $W_{C(\text{off})}$ for turn-off.
2. Calculate (see Fig. 3 and Ref. 21) and add to the table directly following the respective time-related parameters:
 - (a) the total turn-on time t_{on} ;
 - (b) the total turn-off time t_{off} ;
3. In a separate row, calculate the rates of change (i.e. values telling how many times a parameter has changed, not by what amount it has) for all the above parameters (R_G included) with the resistance changing from the smaller to the larger one (not the opposite) (* disregard the smallest of the three resistances).
4. Gather the current tail parameters determined in step 4.3/1.
5. * Plot as function of the gate resistance R_G :
 - (a) the time-related parameters $t_{d(\text{on})}$, t_r , $t_{d(\text{off})}$, t_f (all in one graph);
 - (b) the energy-related parameters $t_{d(\text{on})}$, t_r , $t_{d(\text{off})}$, t_f (both in one graph).

4.5. Result analysis

Time-related parameters

1. Based on results found in the table (* and shown in the plots), determine the effect of the gate resistance value R_G on each of the time-related transistor parameters: $t_{d(on)}$, t_r , t_{on} as well as $t_{d(off)}$, t_f , t_{off} . Consider both the direction and the magnitude of the change (i.e. how many times parameter values change as compared to the rate of change of R_G).
2. Based on turn-off collector current waveforms, as observed in the comparison image obtained in step 4.3/2, state whether the gate resistance has any effect on current tail duration and amplitude and if so, to what extent.
3. Compare the current tail duration t_{tail} and the fall time t_f . Comment on the results of this comparison in respect of practical usefulness of the t_f parameter for evaluating turn-off duration and energy dissipation in the case of the IGBT.

Energy-related parameters

4. Based on the tabulated current tail parameters, calculate the percentage contribution of the $W_{C(off,tail)}$ and $W_{C(off,MOS)}$ components to the total energy dissipated during turn-off $W_{C(off)}$.
State how the current tail-related energy dissipation $W_{C(off,tail)}$ relates to the MOS component turn-off-related energy dissipation $W_{C(off,MOS)}$ (is it approximately equal or much lower or greater, by what ratio?)
5. Based on results found in the table (* and shown in the plots) determine the effect of the gate resistance on each of the energy-related parameters of the transistor $W_{C(on)}$ and $W_{C(off)}$. Consider both the direction and the magnitude of the change (i.e. how many times parameter values change as compared to the rate of change of R_G).
6. Recapitulate whether the circuit designer is able to influence all the dynamic parameters (both time and energy-related) of the IGBT through the gate resistance R_G to the same extent. Which parameters can visibly be influenced less significantly and how does this follow from the physical principles of operation of the IGBT (see Ref. A)?

Comparison of field effect transistors

7. * Based on results from this exercise and from the exercise 3^A, compare the dynamic properties of two types of power field effect transistors, the IGBT and the MOSFET. In the analysis include:
 - (a) the shapes of the waveforms and the consequences they have for time and energy-related parameters;
 - (b) changes of time and energy-related parameters as functions of the gate resistance.

Numerical values as such should not be compared as transistors had different ratings. It is therefore natural that their electrical parameters are different and no conclusion can be drawn out of this fact. Transistors with similar ratings that enable such a comparison to be made, are analysed (in static aspect) in Exercise 5^A.

5. Expected Report Contents

- Oscilloscope image of voltages and current for a full driving voltage pulse, labelled with the current probe current/voltage conversion factor (i.e., the set of waveforms $\{u_{GE}; u_{CE}; i_C\}$)
- Numerical values of characteristic levels with their justification and the calculated threshold values necessary for determination of time-related parameters, according to step 4.1/5
- All the oscilloscope images that have been used to determine the time-related and energy-related parameters of the transistor for the different R_G cases, labelled with the R_G value and the current probe current/voltage conversion factor, put together with plot checks immediately beside or below each of them (i.e., sets of waveforms $\{u_{GE}; u_{CE}; i_C; p_C\}$ for 2 (* 3) R_G cases, separate for turn-on and turn-off, and plot checks obtained in Scilab during energy dissipation computations)
- Table or 2 tables (for turn-on and turn-off) containing obtained numerical results, according to step 4.4/1–3 [i.e., results read out as described in Section 4.2 and calculated in steps 4.4/2–3, 2 (*3) R_G cases, turn-on and turn-off, time-related and energy-related parameters]
- * Plots of time-related and energy-related parameters as function of gate resistance, according to step 4.4/5 (i.e., one plot for time-related parameters and one for energy-related parameters)
- Table containing current tail parameter values, according to step 4.4/4 (i.e., results listed in step 4.3/1 obtained for $R_G = 600 \Omega$)
- Comparative plot of the current tail with each waveform clearly labelled with respect to measurement conditions, according to step 4.3/3 [i.e., collector current waveforms for 2 (* 3) R_G cases, within the interval of current tail occurrence, with identical horizontal (time) scale and synchronised at the beginning of the tail]
- Analysis of the effect of gate resistance on time-related parameters and on current tail parameters, according to steps 4.5/1–2
- Current tail duration and fall time comparison and conclusions, according to step 4.5/3

- Calculation results and analysis of contributions of the different components to the total energy dissipated during turn-off, according to step 4.5/4
- Analysis of gate resistance influence on energy-related parameters, according to step 4.5/5
- Conclusions concerning the possible influence of the designer on time-related and energy-related parameters through the gate resistance, according to step 4.5/6
- * Comparison of MOSFET and IGBT dynamic properties, according to step 4.5/7

6. Required Knowledge

6.1. Prerequisites

- Voltage and current waveforms during IGBT switching (see Fig. 2; Ref. B)
- Physical and technical definitions of IGBT time and energy-related dynamic parameters (see Figs. 2 and 3; Ref. B [21])

6.2. Test scope

1. Insulated Gate Bipolar Transistor: symbol, NPT (symmetric) N-channel IGBT cell cross-section, terminals, drive (control) circuit and main circuit. Two-element equivalent electrical schematics and their location within the semiconductor structure. (see Ref. A)
2. IGBT static output characteristic. Forward conduction state operation: carrier flow paths, channel formation location and excess carrier storage location. Effect of carrier conduction mechanisms on the voltage drop across the structure (referring to the equivalent schematics); main current (I_C) as function of MOS channel current (formula). Positive consequences of introducing (as compared to MOSFET) minority carriers into the N base. (see Ref. A)
3. Voltage, current and collector instantaneous power waveforms during IGBT switching with resistive load. MOS component turn-off and bipolar component turn-off; current tail and its physical origin. Energy dissipated during turn-off and the mutual ratio of its two components, relation to the current tail. Negative consequences of introducing (as compared to MOSFET) minority carriers into the base: unfavourable effects of the current tail on time and energy-related transistor parameters. (see Ref. B, report)
4. Gate resistance effect on the different transistor dynamic parameters: time-related, energy-related (including the two components of the turn-off energy), current tail duration. Relation to IGBT physical operating principles. (see Ref. B, report)

7. References

- [1] Baliga B.J. *Power Semiconductor Devices*. PWS, 1995. ISBN 978-0-53494-0980.
- [21] *IGBT Characteristics*. International Rectifier. Application Note AN-983.