



POWER DEVICES AND SYSTEMS LABORATORY

Exercise 4P

Dynamic Properties of Field-Effect Transistors Insulated Gate Bipolar Transistor

Exercise and manual elaborated by
Łukasz Starzak

Łódź 2019

Contents

B Exercise Introduction	5
1. Exercise Aim and Plan.....	5
2. Insulated Gate Bipolar Transistor	7
2.1. Recommended reading.....	7
C Experiment.....	9
3. Measurements	9
3.1. Test circuit	9
3.2. Preparation for measurements.....	11
Measurement set-up configuration.....	11
Trial measurement	13
3.3. Carrying out waveform measurements	16
Full switching cycle.....	16
Detailed turn-on state and turn-off state observation	16
Effect of gate resistance	18
MOSFET measurements.....	18
Concluding measurements.....	18
D Results	21
4. Processing and Analysing Results.....	21
4.1. Stationary state parameters	21
4.2. Dynamic parameters for the MOSFET	22
Launching Octave.....	22
Determining turn-on state parameters	22
Determining turn-off state parameters.....	24
Result recapitulation	24
Analysis of time-related parameters.....	24
Analysis of energy-related parameters	24
4.3. Dynamic parameters for the IGBT.....	25
Determining turn-on state parameters	25
Determining turn-off state parameters.....	26
Result recapitulation	27
Analysis of time-related parameters.....	27
Current tail	27
Analysis of energy-related parameters	27
4.4. Comparison between IGBT and MOSFET.....	28
E Information	29
5. Required Knowledge.....	29
5.1. Prerequisites	29
5.2. Test scope.....	29
6. References	30

Exercise Introduction

1. Exercise Aim and Plan

The aim of this exercise is to investigate the operation of power transistor in dynamic states. Two devices will be compared with each other in this respect: a bipolar one, IGBT, and a unipolar one, MOSFET. As both are voltage and charge-controlled, any differences observed between them will result exclusively from the different conduction mechanisms. Nevertheless, the effect of the control circuit of a transistor on its principal circuit will be analysed, too. In this regard, switching times will be measured. Their differing values obtained will in turn make it possible to determine the relation between these times and the heat dissipated in a semiconductor switch.

Moreover, this exercise is an opportunity to get acquainted in detail with the operating principles of one of the most popular power semiconductor device, the Insulated Gate Bipolar Transistor (IGBT). The particular device selected for this purpose belongs to a standard type, which has not been optimised in any specific respect. Thanks to this choice, any features characteristic to IGBTs in general will be clearly visible.

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 experimental circuit is presented in Fig. 1. Through blue screw terminal blocks on the circuit's panel, it is possible to insert in the circuit:

- a gate resistor R_G , through the 2-pin terminal block,
- a load resistor (receiver) R_L , through the 4-pin terminal block (only one pair of its terminals will be used while the other one will be shorted),
- the transistor under investigation T, through the 3-pin terminal block, whose connection to the circuit must be determined by comparing connections shown in Fig. 1 to the ones shown on the circuit's panel.

An IRFB9N60A MOSFET and an IRG4BC20S IGBT will be investigated in this exercise. One of the large-size 50-watt resistors enclosed in a metal heat sink, available at the laboratory stand, will be used as the receiver. On the other hand, standard small-size 0.25 to 0.6-watt resistors will be used as gate resistors.

In order to eliminate the effect of self-heating on the operation of the transistor under investigation as well as to enable a large current to flow without the risk of the transistor thermally breaking down, measurements will be performed using single switching pulses for the transistor (which will turn it on and, after a short while, turn it off). A rectangular pulse of the u_g voltage is generated each time the red button on the circuit's panel is pressed (the K switch in Fig. 1); the pulse duration t_p is a dozen microseconds and its amplitude is roughly equal to the control circuit supply voltage U_{GG} .

Thus, it is necessary to generate a switching pulse after each change of settings. This is also valid when changes are only made on a measurement device (oscilloscope or current probe). Only after a new pulse is generated will the oscilloscope record waveforms using the new settings and their changes will have any effect. Before this is done, it may appear that oscilloscope data have changed (e.g. waveforms have been zoomed horizontally by decreasing the time base), but in fact this is not true. In the oscilloscope's memory, data recorded with previous settings are still present; it is only that the spacing between points has been increased on the screen. This kind of zoom may

be compared to a photo camera digital zoom: it does not cause the image to be recorded with greater accuracy, but just to be stretched.

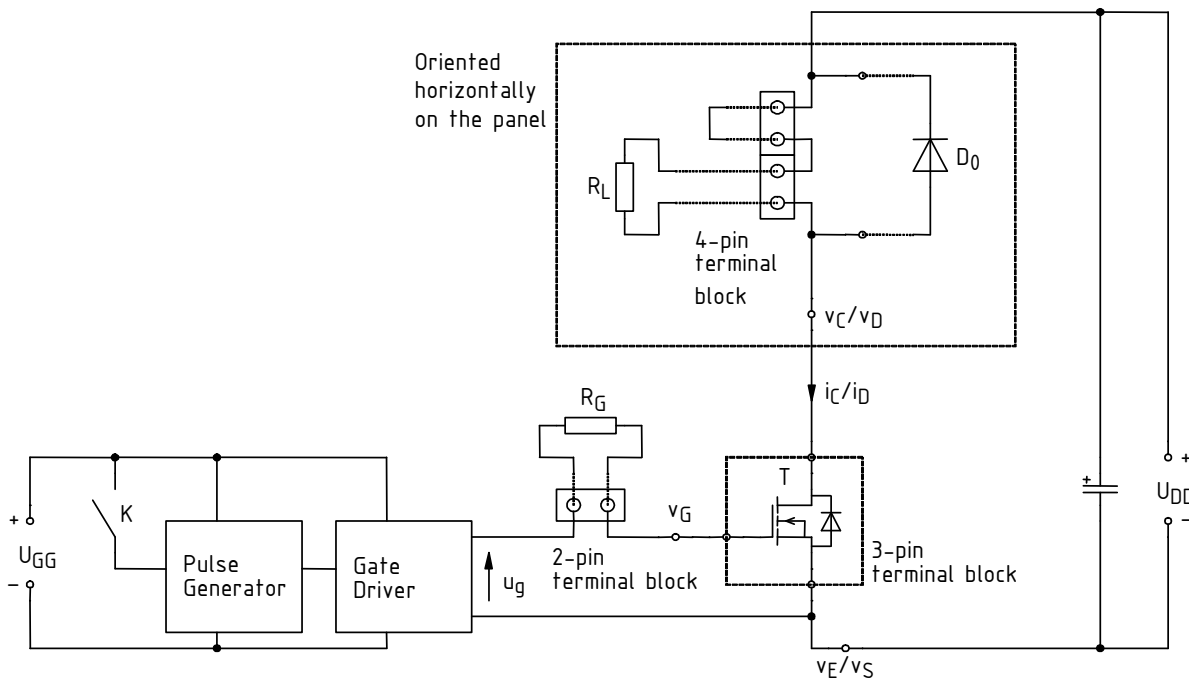


Fig. 1. Schematic diagram of the experimental circuit (as for screw terminal blocks, only electrical connections are represented, not their true layout on the circuit's panel)

Two two-section power supplies will be used to energise the experimental circuit:

- one with sections operating independently (only one of them being used), for the control circuit (U_{GG});
- one with sections connected in series, which will enable obtaining a higher voltage, for the power loop (U_{DD}).

The experimental circuit enables measurements of inter-terminal voltages and of the principal current of the device under investigation. Voltage measurements are performed using voltage probes appropriately connected to banana sockets labelled as v_E/v_S , v_G and v_C/v_D in Fig. 1. Banana connectors with leads that enable a probe to be attached are provided for this purpose. These connectors may be freely moved depending on present measurement needs.

Current measurements are performed by clamping a current probe around the wire fragment led above the front panel and marked as i_C/i_D in Fig. 1. The arrow on the probe's casing indicates the direction assumed to be positive. The probe should be so oriented that this direction is in accordance with the true one.

Oscilloscope data are recorded using the OpenChoice Desktop application, which is accessible from the Start Menu under *Pomiary*, following the procedure described further in this manual.

3.2. Preparation for measurements

Measurement set-up configuration

The block diagram of the measurement set-up is presented in Fig. 2. It should be assembled in the way described below and following the order of actions specified.

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

1. Switch the computer on. After logon completes, switch the oscilloscope on and, if necessary, set up its connection to the computer following a manual available at the laboratory stand.
2. Bring power supply to the experimental circuit:
 - (a) make sure that both power supplies are switched off;
 - (b) using two buttons in the middle of the front panel, set the operation modes for supply sections:
 - on one power supply, which will be used for the control circuit (just one adjustable section necessary): independent,
 - on the other power supply, which will be used for the power loop (two adjustable sections necessary): series;
 - (c) turn all the knobs of both power supplies down to zero (extreme anticlockwise position);
 - (d) using banana-terminated wires, connect the “-” and “+” sockets of one of the adjustable sections of the control circuit power supply [see sub-step (b)] to the U_{GG} sockets on the circuit’s panel, keeping the polarity as indicated on the power supply;

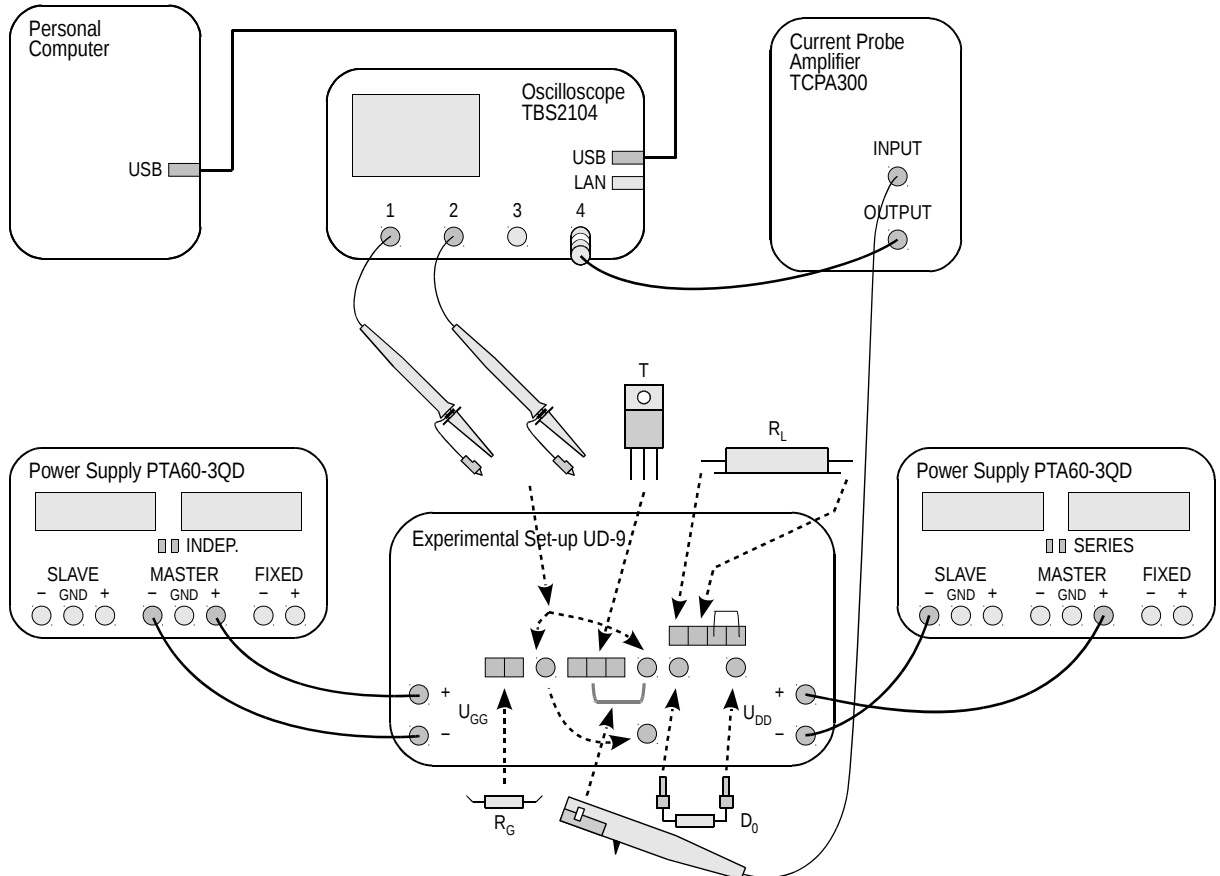


Fig. 2. Block diagram of the measurement set-up for drain-to-source resistance measurement

- (e) using banana-terminated wires, connect the extreme sockets of the power loop supply (i.e. the “-” socket of the Slave section and the “+” socket of the Master section) to the U_{DD} sockets on the circuit’s panel, keeping the polarity as indicated on the power supply.
- Using a multimeter operating in its resistance measurement mode, measure and write down resistances R_G of the two gate resistors available (small ones, 0.25 to 0.6 W).
 - In the two-pin blue terminal block, mount the resistor that has shown a resistance of about 470 Ω .

To avoid damaging transistors’ gates by electrostatic discharge, handle them only after grounding yourself (e.g. by touching the ground of any oscilloscope input)! Do not touch a transistor’s leads; handle it by its metal base instead.

- Mount the IGBT to be investigated in the three-pin terminal block on the circuit’s panel, according to the circuit schematic (compare Fig. 1 to the drawing on the panel) and to this transistor’s terminal arrangement shown in its data sheet. Tighten all the three mounting screws.
- From the web page, obtain and write down the power loop supply voltage U_{DD} and the desired load current I_o .
- Mount necessary components in the blue terminal blocks on the circuit’s panel, tightening mounting screws:
 - short one of the terminal pairs of the four-pin block with a short bare wire available at the laboratory stand (unless this is already done);
 - applying Ohm’s law, calculate such a load resistor resistance R_L that with the power loop supply voltage U_{DD} obtained in step 6, after transistor is turned on, the current I_o determined in step 6 flows in this loop (for this sake, assume that the transistor is an ideal switch, i.e. that the on-state resistance between its main terminals is zero);
 - between the other terminal pair of the four-pin block, connect a power resistor (50-watt, in a metal casing, with short lead wires) with the resistance closest to the value calculated above;

Values of electronic component parameters, normally in the form of “a.b U,” where a is an integer part, b is a decimal part and U is a unit, are frequently written as “aUb.”

The metal casing of the resistor cannot at any time touch any other metallic parts. This might result in a short-circuit and a consequent damage of the circuit and of the device under investigation!

- in parallel to the R_L resistor, in the sockets located under the 4-pin terminal block, mount the clamping diode D_o available at the laboratory stand (with banana connectors on its leads) keeping diode polarity as shown in Fig. 1 (the cathode being marked with a strip on the case).
- Connect two 10:1 attenuation voltage probes so that the gate-source voltage u_{GE} is measured in the oscilloscope’s channel 1 and the drain-source voltage u_{CE} is measured in channel 2. If just one of the probes has a ground connector available, it should be used to measure the u_{CE} voltage.

Warning!

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

2. During measurements, do not touch parts where the power loop supply voltage is present (especially the collector/drain potential connector v_C/v_D , the transistor’s metal base, the load resistor’s and the clamping diode’s leads).

3. Before proceeding with the following step, connections must be checked by the teacher!

4. Before executing each of the steps 9 and 10, read them first in their entirety, including any comments below!

9. Switch the control circuit power supply on. Slightly increase the current limiting threshold (*Current* knob) until the red current limiting indicator (*C.C.*) goes out.

Set the control circuit supply voltage (*Voltage* knob) to 15 V; if current limiting activates in the course of setting, decrease the voltage first, increase the current limiting threshold and only then re-try increasing the voltage.

Under correct circuit operation, the power supply's ammeter should indicate a current consumption of the order of tens of milliamps. Should you observe anything different during or after setting, switch the power supply off immediately and ask the teacher to re-check your circuit.

Be careful not to exceed the voltage of 18 V at any time while setting; otherwise integrated circuits might be damaged.

10. Energise the power loop:
- switch the power loop supply on;
 - slightly increase the current limiting thresholds in both sections of the power loop supply (*Current* knobs) until red current limiting indicators (*C.C.*) go out;
 - using the Master section *Voltage* knob (which simultaneously adjusts both sections in the series mode), set the power loop supply voltage to the value determined in step 6 (as the circuit is supplied from a series connection of sections, it is the sum of indications of *Slave* and *Master* section voltmeters that should be equal to the required value); in case current limiting activates, act as in step 9;
- a red LED indicator should light up on the circuit's panel.

Under correct circuit operation, the power supply's ammeter should not indicate any current consumption apart from a constant current of the LED indicator (about 0.02 A) and a transient charging current of a stabilising capacitor found inside the circuit (not more than 0.05 A). Should you observe anything different during or after setting, switch the power supply off immediately and ask the teacher to re-check your circuit.

11. 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_4p_tbs2014.set*;
 - click *Send Settings* (not *Send to multiple*);
 - return to the *Screen Capture* tab.

Trial measurement

12. Generate a switching pulse for the transistor by pushing the red button on the circuit's panel. On the oscilloscope, the message "Trig'd" (Triggered) should momentarily appear above the graticule and the u_{GE} voltage waveform should be displayed. If this does not happen, ask the teacher to check oscilloscope settings.
13. Adjust (generating a switching pulse after each setting change is made) the time base and the trigger event position (*Horizontal Scale* and *Horizontal Position* knobs) so that one pulse of the u_{GE} voltage is visible in its entirety (cf. Fig. 3) and occupies most of the screen horizontally.
14. Using the *2* button, display the waveform from channel 2, i.e. the u_{CE} voltage. Check whether the waveform is generally correct (see Fig. 3).

Buttons labelled with channel numbers 1 to 4 cause toggled displaying and hiding the waveform from a given oscilloscope channel. When a given waveform is displayed, this is indicated by an arrow showing the zero level left of the graticule as well as by a corresponding channel label "CHx" under the graticule.

15. If any waveform extends beyond the screen (ignoring possible short spikes), adjust the appropriate channel gain and zero level position (*Vertical Scale* and *Vertical Position* knobs).

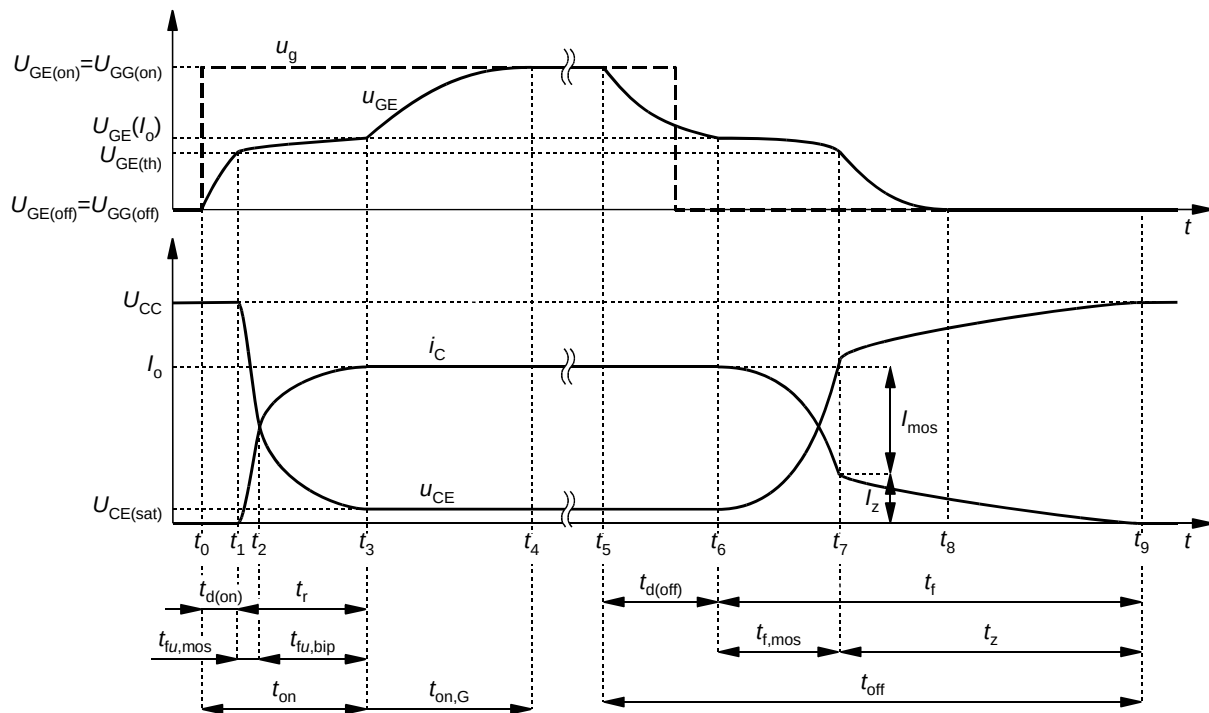


Fig. 3. Voltage and current waveforms during IGBT switching

16. Using the 4 button, display the waveform from channel 4 (its current shape being unimportant for now).
17. Configure the current probe and its connection to the oscilloscope following a manual for current probes available at the laboratory stand. Obligatorily read and apply oscilloscope configuration guidelines given in that manual.

At the appropriate moment:

- connect the amplifier's output to the oscilloscope's channel 4;
 - initially set the current/voltage conversion ratio to a value enabling a current waveform with the amplitude I_0 determined in step 6 to be measured and displayed on the oscilloscope (see information about current probe amplifier operation given in the current probe manual).
18. Set DC coupling on the current probe amplifier.
 19. Clamp the probe around the appropriate wire fragment so that the collector current i_c is measured and that its measured sense is in accordance with the true one (considering the connection diagram shown on the experimental circuit's panel).
 20. Generating switching pulses, adjust measurement path gain and waveform position (*Vertical Scale* and *Vertical Position* knobs) so that the current waveform can be optimally seen, i.e. that it fills the screen to the maximum extent vertically but does not extend beyond it. Check whether the waveform is correct (see Fig. 3).
 21. If, due to the imperfect operation of the current probe, the off-state current value seen on the oscilloscope—which is known to be imperceptibly small at the present graticule scale—is not located exactly at the zero level (indicated with an arrow left of the graticule) of the relevant oscilloscope channel, introduce the necessary correction:
 - (a) on the oscilloscope, change the triggering mode to automatic by pushing the *Trigger Menu* button, pushing the *Mode* screen button, selecting *Auto* with the *Multipurpose* knob and accepting by pushing the knob;
 - (b) temporarily hide the waveforms from channels 1 and 2;

- (c) using the *Manual Balance* $\hat{\uparrow}/\hat{\downarrow}$ buttons on the probe amplifier, shift the current waveform as appropriate (due to the large graticule constant of the current, a button must be kept pressed for a few or a dozen of seconds in order for the shift to become perceptible);
- (d) on the oscilloscope, restore the normal triggering mode by pushing the *Trigger Menu* button, pushing the *Mode* screen button, selecting *Normal* with the *Multipurpose* knob and accepting by pushing the knob;
- (e) display back the waveforms from channels 1 and 2.

Failure to perform the above step may lead to erroneous results.

22. Generate a switching pulse. Check if the current pulse amplitude observed on the oscilloscope is approximately equal to the value determined in step 6. In case of discrepancy, make sure that the settings of the respective oscilloscope channel are in accordance with requirements given in the current probe manual. If this does not help, ask the teacher to re-check the circuit and measurement equipment settings.

Skipping the above step may cause a lot of trouble during result elaboration!

3.3. Carrying out waveform measurements

Full switching cycle

1. Generate a switching pulse train. If needed, adjust gains and zero level positions of the particular channels (*Vertical Scale* and *Vertical Position* knobs) so that each waveform, starting from its zero level (indicated with an arrow left of the graticule) and up to its maximum value, fills the entire screen to the maximum extent vertically but does not extend beyond it (still ignoring possible short spikes).
2. Make sure that the pulse of the u_{GE} voltage is visible in its entirety and occupies most of the screen horizontally; if not, adjust (generating a switching pulse after each setting change is made) the time base and the trigger event position (*Horizontal Scale* and *Horizontal Position* knobs) as appropriate.
3. Record a complete set of the three waveforms, u_{GE} , u_{CE} and i_{DC} (all together), in a graphical form:
 - in the OpenChoice Desktop application, go to 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 (not with the *Enter* key, as this would cause another activation of the *Save As* button).

Detailed turn-on state and turn-off state observation

4. Display the instantaneous collector power loss p_C (equal to the product of collector current and collector-emitter voltage) waveform:
 - display the mathematical operation result waveform by pushing *M*,
 - using an appropriate screen button and the *Multifunction* knob, select the operation of multiplication (\times),
 - set appropriate channels as arguments *Source 1* and *Source 2* for the multiplication.
5. Record waveforms enabling time-related and energy-related dynamic parameters for transistor turn-on (not any other operating state) to be determined:
 - (a) generating switching pulse trains, modify the time base (*Horizontal Scale*) and the trigger event position (*Horizontal Position*) so that the transistor's turn-on process (not any other operating state) can be observed with the highest accuracy possible, both in the principal and in the control circuit, i.e. all along the $t_{on,G}$ interval (see Fig. 3);
 - (b) make sure that all crossing moments of all thresholds necessary to determine all the time-related turn-on parameters (see Fig. 4) are visible on the screen; if not, adjust the time base (*Horizontal Scale*) and the trigger event position (*Horizontal Position*);
 - (c) make sure that channel settings still meet the requirements of given in step 1, however, taking possible overvoltages into consideration now; if not, modify these settings according to step 1;
 - (d) if the mathematical operation waveform settings menu is not displayed on the screen now, display it by pushing the *M* button;
 - (e) push the *Vertical Scale* screen button and with the *Multipurpose* knob, adjust the p_C waveform scale so that it fills the entire screen to the maximum extent vertically but does not extend beyond it;
 - (f) record a complete set of the four waveforms, u_{GE} , u_{CE} , i_C and p_C (all together), in a numerical form:
 - in the OpenChoice Desktop application, go to the *Waveform Data Capture* tab,

- click *Select Channels* and tick channels CH1, CH2, CH4 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 (not with the *Enter* key, as this would cause another activation of the *Save As* button).

Later on, selecting channels again will not be necessary. Therefore, instead of the *Select Channels* button, the *Get Data* one should be used directly.

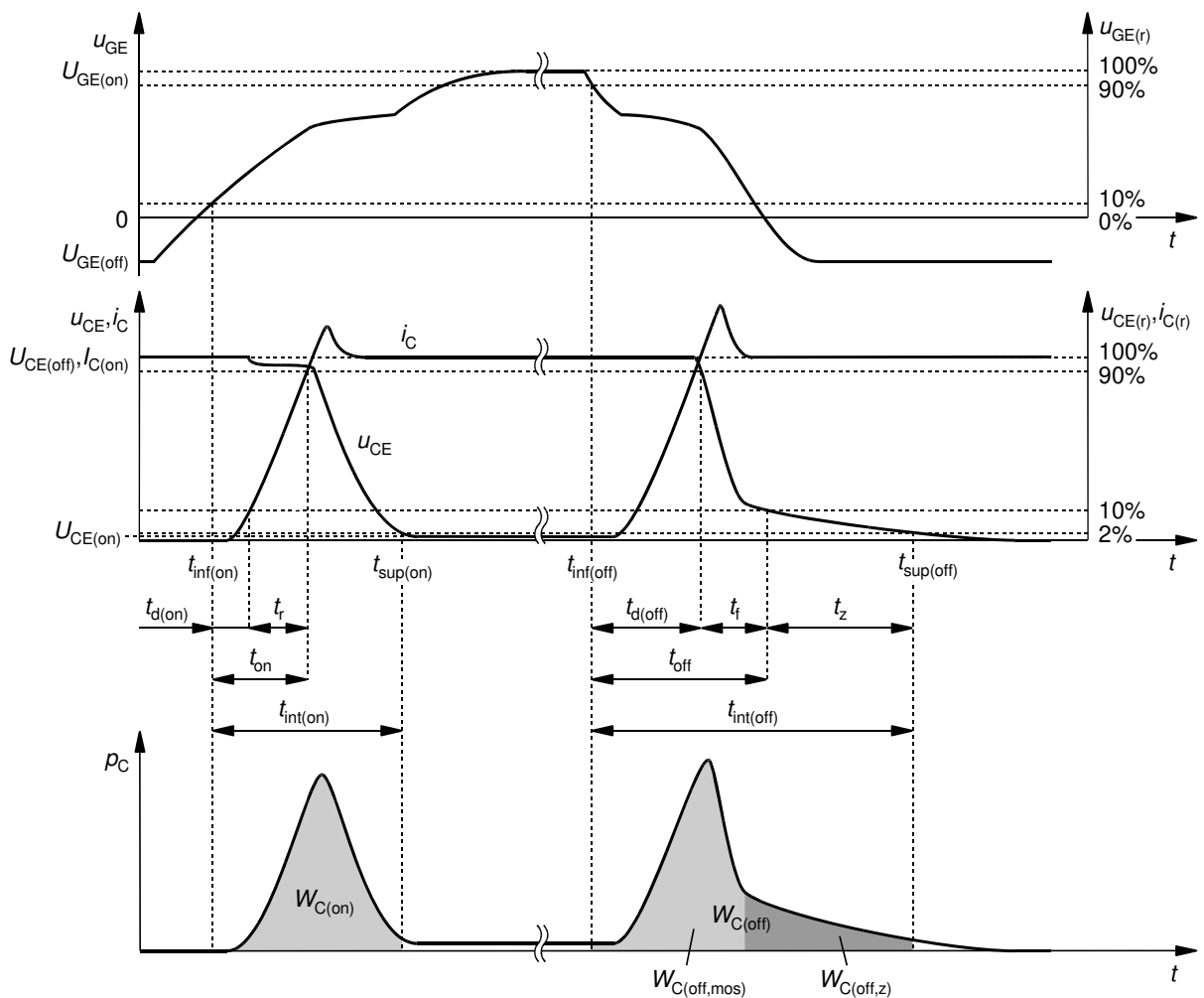


Fig. 4. Technical definitions of IGBT time-related and energy-related parameters according to IEC 60747-9

- Record waveforms enabling time-related and energy-related dynamic parameters for transistor turn-off to be determined:
 - before taking any other action, switch the oscilloscope to falling-edge triggering with the u_{GE} waveform by pushing *Trigger Menu* and then the *Slope* screen button to change the respective option to \searrow ;

Failure to carry out the above sub-step will make exercise realisation considerably longer.

- repeat step 5 in its entirety, i.e. all of the included sub-steps [not only some selected ones, with the exception described in the remark under sub-step 5(f)], except that when assessing

the correctness of the observed waveforms, obviously the turn-off process should be considered instead of the turn-on one, i.e. the t_{off} interval in Fig. 3 and the appropriate threshold crossing moments in Fig. 4.

In most cases, failure to carry out sub-steps 5(a) and (b) will make it impossible during result elaboration to obtain required results from the image recorded.

Effect of gate resistance

7. Bring the power loop supply voltage to zero (do not switch the power supply off).
8. Replace the gate resistor R_G to one with a resistance of about 220 Ω .
9. Restore the previous power loop supply voltage (the value applied in step 3.2/10).

While restoring voltage, current limiting may temporarily activate. It should deactivate naturally after the stabilising capacitor inside the experimental circuit is re-charged. This should not take more than a few seconds.

10. Obtain and record waveforms under the new conditions by repeating steps 5 to 6.

MOSFET measurements

11. Bring the power loop supply voltage to zero.
12. Restore the gate resistor R_G of about 470 Ω .

While handling transistors, precaution measures specified earlier must be taken.

13. From the three-pin terminal block on the circuit's panel, dismount the IGBT and mount the MOSFET to be investigated there, according to the circuit schematic (compare Fig. 1 to the drawing on the panel) and to this transistor's terminal arrangement shown in its data sheet.

Before proceeding with the following step, connections must be checked by the teacher!

14. Restore the previous power loop supply voltage (the value applied in step 3.2/10), continuously checking if the circuit does not exhibit a constant current flow (see the remark under step 9); if constant current flow is observed, switch the power supply off and ask the teacher to re-check your circuit.
15. With the *M* button, remove the instantaneous power waveform from the screen.
16. Obtain and record waveforms as for the IGBT by repeating steps 1 to 10, while considering the waveforms of u_{GS} , u_{DS} , i_D and p_D , respectively. Plots that correspond to Figs. 3 and 4 and facilitate assessing the correctness of waveforms observed as well as of oscilloscope scale settings, are presented in Figs. 5(a) and 5(b), respectively.

Concluding measurements

17. Bring the power loop supply voltage down to zero. Wait until the red LED indicator goes out on the circuit's panel.
18. Bring the control circuit supply voltage down to zero.
19. Switch the power supplies off and remove connections in the set-up; however, do not unplug voltage probes from the oscilloscope, the current probe from its amplifier or the probe amplifier from the oscilloscope.
20. Dismount the load resistor, the gate resistor and the transistor; do not remove the bare shorting wire from the four-terminal block. Tighten back all screws in the now unoccupied terminal blocks.

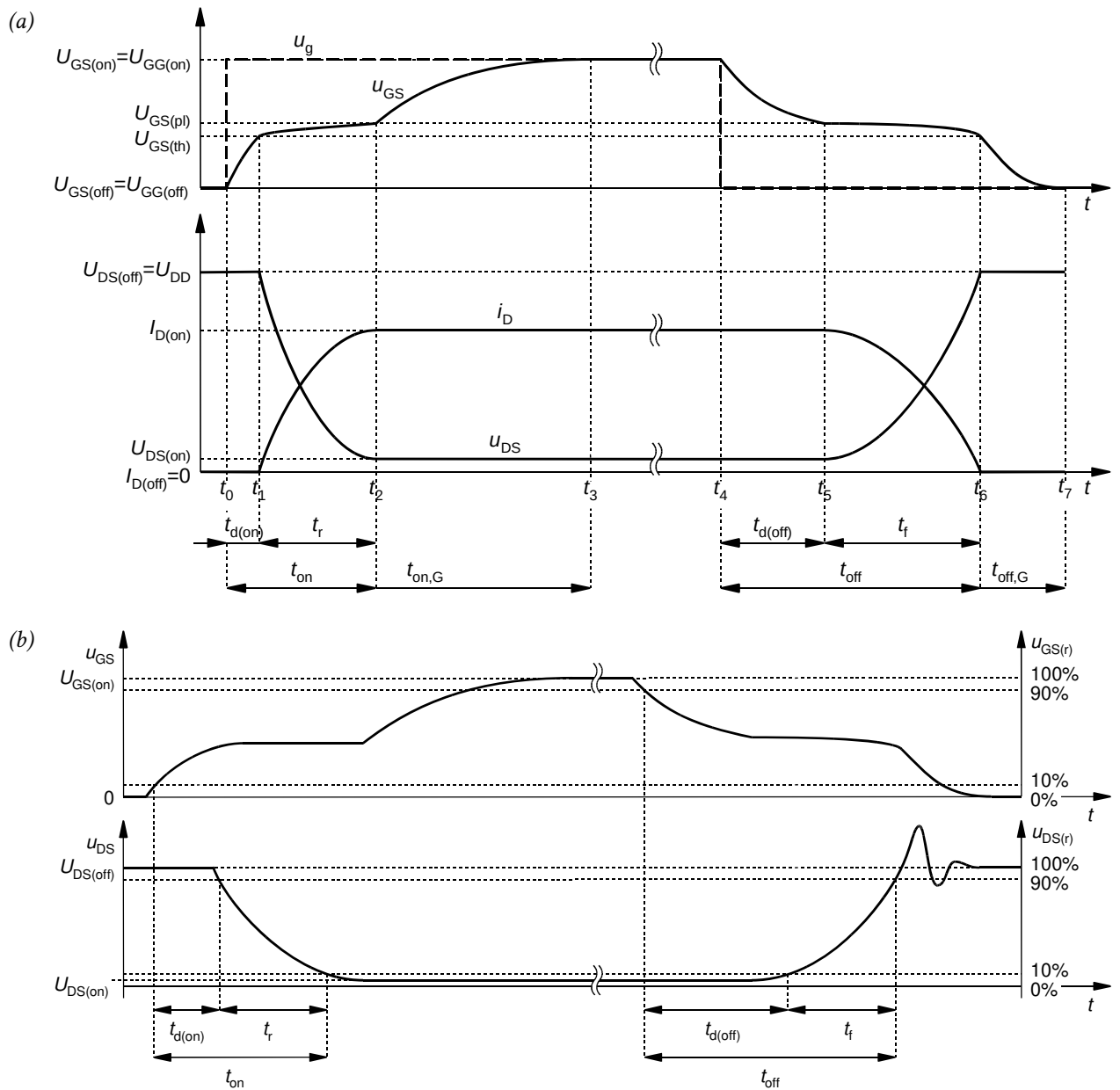


Fig. 5. Power MOSFET switching under resistive load: (a) voltage and current waveforms; (b) technical definitions of time-related parameters according to IEC 60747-8-4

4. Processing and Analysing Results

4.1. Stationary state parameters

1. Insert your oscilloscope images recorded in a graphical form as indicated in Part 1 of the report.
2. Fill in Part 1 of the report.

4.2. Dynamic parameters for the MOSFET

Launching Octave

1. Run the numerical computing package Octave.
2. Click the *Browse Directories* icon and change the working folder to the one containing oscilloscope data recorded using OpenChoice Desktop.
3. 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');
```

Determining turn-on state parameters

4. Obtain data recorded in the numerical form (CSV format) for the MOSFET transistor, for the gate resistance of about 470Ω , for the turn-on state:

- (a) read an appropriate file by executing the command:

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

- (b) to simplify further result processing, create four variables and assign indices of the particular waveforms recorded (u_{GS} , u_{DS} , i_D and p_D) to these variables by executing the following series of commands:

```
iUgs=oscwfmidx(OscRecord,'channel_label_ugs')
iUds=oscwfmidx(OscRecord,'channel_label_uds')
iId=oscwfmidx(OscRecord,'channel_label_id')
iPd=oscwfmidx(OscRecord,'channel_label_pd')
```

The parameters *channel_label_ugs*, *channel_label_uds*, *channel_label_id* and *channel_label_pd* represent labels of oscilloscope channels where the u_{GS} , u_{DS} , i_D and p_D waveforms were measured, respectively. If probes were connected in accordance with this manual (steps 3.2/8 and 17), then these were the channels 1, 2, 4 and M (the result of the arithmetic operation of multiplication) which the oscilloscope used labels as *CH1*, *CH2*, *CH4* and *MATH*, 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.

5. To enhance future result quality:

- (a) denoise data by executing the command:

```
OscRecord=oscdenoise(OscRecord);
```

- (b) eliminate a possible zero level shift of the current probe by executing the command:

```
OscRecord=oscfixcurrentzero(OscRecord,iId,iUds,iPd);
```

The function *oscfixcurrentzero* will provide correct results only if the waveforms were recorded in accordance with the manual, i.e. the observation window covers one complete switching process from its beginning until steady-state waveform levels are reached and it does not include any other operating state. This also applies to most of the functions used further in result processing.

6. Determine values of the time-related parameters $t_{d(on)}$ and t_r according to their normative definitions [see. Fig. 5(b) and, if in doubt, its textual description in Manual 3P, sub-section 2.2]: for each of these parameters:

- (a) execute the command

```
oscdeftax2rel(OscRecord,waveform_index_1,threshold_1,
waveform_index_2,threshold_2,true,true)
```

The parameters *threshold_1* and *waveform_index_1* represent a relative threshold (expressed as a fraction of unity, i.e. 10% must be entered as 0.1) that marks the beginning of an appropriate time interval and the index of the waveform (stored in an appropriate variable, *iUgs*, *iUds*, *iId* or *iPd*) which this threshold applies to, according to the normative definition of a given time-related parameter. By analogy, *threshold_2* and *waveform_index_2* represent a relative threshold that marks the end of that time interval and the index of the waveform which this threshold applies to. The first of the *true* values indicates that—according to time-related parameters' definitions—relative values should be calculated by referencing absolute values to zero. The second value of *true* causes a graph to be displayed showing the coordinates of the beginning and the end of the time interval considered, allowing result credibility to be visually assessed.

- (b) based on the check plot displayed, make sure that the value obtained has been determined in accordance with the normative definition of the given transistor parameter;
if not, determine the cause of the result being incorrect (e.g. incorrectly defined thresholds, incorrect waveform indices, incorrect file used which does not contain data for the transistor or the operating state to be analysed, incorrectly recorded waveforms); if possible, eliminate this cause and repeat step (a); should waveforms be incorrect to an extent making it impossible for the appropriate time interval to be detected automatically, try determining the given transistor parameter manually based on plot axis labels and using the zoom function;
- (c) after validating the result, insert the check plot (or, in the case of determining the result manually, a plot with the time interval marked by yourself) in the appropriate space provided in Part 2 of the report.
7. Determine the value of the energy $W_{D(on)}$ as the integral of the instantaneous power loss p_D according to its normative definition (see Manual 6P, Sub-chapter 2.2), except that, to prevent the extremes of the switching process from being omitted due to the slow variation of the u_{DS} waveform, 5% thresholds should be applied instead of 10% ones as specified in the standard:

- (a) execute the command:

```
oscintegral3rel(OscRecord,iPd,waveform_index_1,threshold_1,
waveform_index_2,threshold_2,true,true)
```

- (b) based on the check plot displayed, make sure that the value obtained has been determined in accordance with the normative definition of the transistor parameter considered;
if not, determine the cause of the result being incorrect (e.g. incorrectly defined thresholds, incorrect waveform indices, incorrectly recorded waveforms); if possible, eliminate this cause and repeat step (a); should waveforms be incorrect to an extent making it impossible for the appropriate time interval to be detected automatically, try determining the coordinates of the extremes of this interval manually based on plot axis labels and using the zoom function and then calculate the integral according to the normative definition using the *oscintegral* function described in step 4.3/9;
- (c) after validating the result, insert the check plot (or, in the case of determining the result manually, a plot displayed by the *oscintegral* function together with a graph of the appropriate waveforms with the time interval marked by yourself) in the appropriate space provided in Part 8 of the report.
8. Determine the peak value of the drain power loss $P_{D(on)pk}$ as the maximum value from the power waveform by executing the command:

```
max(OscRecord.Waveforms(iPd).Values.y)
```

9. Repeat steps 4 to 8 [if measurements were conducted in accordance with the manual, there is no need to repeat step 4(b)] for the gate resistance of about 220 Ω .

Determining turn-off state parameters

10. Proceeding by analogy to steps 4 to 8 [if measurements were conducted in accordance with the manual, there is no need to repeat step 4(b)], but this time considering the turn-off state, for the gate resistance of about 470Ω , determine this state parameter values: $t_{d(off)}$, t_f , $W_{D(off)}$ and $P_{D(off)pk}$.

11. Repeat step 10 for the gate resistance of about 220Ω .

After completing the above actions, do not close Octave as it will be needed to process results for the IGBT in Sub-chapter 4.3.

Result recapitulation

12. Include the parameters determined until now, together with the gate resistor values R_G measured, in appropriate tables in Part 2 of the report. To make result analysis possible, all the times for all the cases must be expressed using the same unit; by analogy, this also applies to all the power values and all the energy values (including ones that will be calculated later).

13. Calculate and enter in the final row of each table the rate of decrease of the value (a quotient expressing how many times they changed, not a difference expressing by what amount they did) of every parameter (as found in all the columns, R_G included) when resistance was changed from a higher one to a lower one (not the other way around, so that numbers greater than 1 are obtained in most cases), i.e.

$$q_{\text{decr(LH)}}(X) = \left(\frac{X(R_{GL})}{X(R_{GH})} \right)^{-1} = \frac{X(R_{GH})}{X(R_{GL})} \quad (4.1)$$

where X represents each consecutive transistor parameter while R_{GH} and R_{GL} represent the higher and the lower resistance value R_G , respectively (a value of $q_{\text{decr(LH)}}$ lower than one would mean that the given parameter increased, not decreased, due to the decrease of R_G).

In the table, show values with an accuracy of two significant digits (not more, as this would be unjustified in the context of measurement uncertainty).

14. In order to make result interpretation easier and more strict, calculate consecutive powers of the $q_{\text{decr(LH)}}$ quotient for the resistance R_G , i.e. $[q_{\text{decr(LH)}}(R_G)]^\alpha$, for $\alpha \in \{0; 0.5; 1; 1.5; 2\}$. Include your results in the table found in Part 2 of the report, with an accuracy of two significant digits.

Analysis of time-related parameters

15. Complete Part 2 of the report.

Analysis of energy-related parameters

16. Fill in Part 3 of the report.

4.3. Dynamic parameters for the IGBT

Determining turn-on state parameters

1. Obtain data recorded in the numerical form (CSV format) for the IGBT transistor, for the gate resistance of about 470Ω , for the turn-on state:

- (a) read an appropriate file by executing the command:

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

- (b) to simplify further result processing, create four variables and affect them with indices of the particular waveforms recorded (u_{GE} , u_{CE} , i_C and p_C) by executing the following series of commands:

```
iUge=oscwfmidx(OscRecord,'ozn_kana_u_uge')
iUce=oscwfmidx(OscRecord,'ozn_kana_u_uce')
iIc=oscwfmidx(OscRecord,'ozn_kana_ic')
iPc=oscwfmidx(OscRecord,'ozn_kana_pc')
```

If probes were connected in accordance with this manual (steps 3.2/8 and 17), then the above waveforms were measured in the channels 1, 2, 4 and M, respectively, which the oscilloscope used labels as *CH1*, *CH2*, *CH4* and *MATH*.

2. To enhance future result quality, denoise data and eliminate zero level shift of the current probe by executing the commands:

```
OscRecord=oscddenoise(OscRecord);
OscRecord=oscfixcurrentzero(OscRecord,iIc,iUce,iPc);
```

3. Determine values of the time-related parameters $t_{d(on)}$ and t_r according to their normative definitions [see Fig. 4 and, if in doubt, its textual description in Ref. [21], Section 8.5]: for each of these parameters:

- (a) execute the command (using appropriate waveforms and applying appropriate thresholds):

```
oscdeletax2rel(OscRecord,waveform_index_1,threshold_1,
waveform_index_2,threshold_2,true,true)
```

- (b) based on the check plot displayed, make sure that the value obtained has been determined in accordance with the normative definition of the given transistor parameter; if not, act according to step 4.2/6(b);
- (c) after validating the result, insert the check plot (or, in the case of determining the result manually, a plot with the time interval marked by yourself) in the space provided in Part 8 of the report.

4. Determine the value of the energy $W_{C(on)}$ as the integral of the instantaneous power loss p_D according to its normative definition [see Fig. 4 and, if in doubt, its textual description in Ref. [21], Section 8.5], except that, due to the possibility of the on-state voltage $U_{CE(on)}$ being continuously higher than 2% of the off-state voltage $U_{CE(off)}$ as a result of applying a blocking voltage much lower than the rated voltage of the transistor investigated, relative values should be calculated by referencing absolute values to low steady-state values instead of zero, i.e. *false* should be given as the penultimate function parameter value:

- (a) execute the command:

```
oscintegral3rel(OscRecord,iPc,waveform_index_1,threshold_1,
waveform_index_2,threshold_2,false,true)
```

- (b) based on the check plot displayed, make sure that the value obtained has been determined in accordance with the normative definition of the transistor parameter considered; if not, act according to step 4.2/7(b);
 - (c) after validating the result, insert the check plot (or, in the case of determining the result manually, a plot displayed by the *oscintegral* function together with a graph of the appropriate waveforms with the time interval marked by yourself) in the appropriate space provided in Part 8 of the report.
5. Repeat steps 1 to 4 [if measurements were conducted in accordance with the manual, there is no need to repeat step 1(b)] for the gate resistance of about 220 Ω .

Determining turn-off state parameters

6. Proceeding by analogy to steps 1 to 4 [if measurements were conducted in accordance with the manual, there is no need to repeat step 1(b)], but this time considering the turn-off state, for the gate resistance of about 470 Ω , determine this state time-related parameter values: $t_{d(off)}$ and t_f .
7. Proceeding by analogy to step 4, determine the value of the energy-related parameter $W_{C(off)}$ together with limit coordinates of the respective integration interval, $t_{inf(off)}$ and $t_{sup(off)}$ (see Fig. 4), by executing the command:

```
[WCoff,tinffoff,tsupoff]=oscintegral3rel(OscRecord,iPc,
waveform_index_1,threshold_1,waveform_index_2,threshold_2,false,true)
```

The variable *WCoff* will store the principal result of the above function, representing the value of the integral of the *p_C* waveform. The variables *tinffoff* and *tsupoff* will contain coordinates of the beginning and the end of the integration interval, respectively.

8. * Calculate the length of the integration interval $t_{int(off)}$ as the difference between the coordinates $t_{sup(off)}$ and $t_{inf(off)}$.
9. Determine parameters of the current tail:
 - (a) making use of plot axis labels, establish the coordinate of the beginning of the true current tail, i.e. of the time point t_7 according to Fig. 3 (the point of change in the fall rate of the i_C current, not the end of the t_f interval in Fig. 4);
 - (b) obtain the magnitude of the current tail I_z (see Fig. 3) as the value of the i_C current at the time point t_7 , by executing the command:

```
oscyatx(OscRecord,iIc,t7)
```

The function *oscyatx* returns the value of the waveform identified by the index given, for a time coordinate specified by the last parameter. The numerical value established in sub-step (a) should be substituted for t_7 .

visually check the result obtained by roughly comparing it against the plot; in case of discrepancy, determine and eliminate its cause;

- (c) calculate the length of the true (physical) current tail $t_{z(phys)}$ according to Fig. 3 (not the normative parameter t_z of Fig. 4) as the difference between the coordinates $t_{sup(off)}$ and t_7 ;
- (d) determine the energy related to the current tail, $W_{C(off,z)}$ (cf. Fig. 4) as the integral of the instantaneous power p_C over the time interval from t_7 to $t_{sup(off)}$, i.e. over the time interval $t_{z(phys)}$, by executing the command:

```
oscintegral(OscRecord,iPc,t7,tsupoff,true)
```

The function *oscintegral* returns the value of the waveform identified by the index given, for a time coordinate specified by the last parameter. The numerical value established in sub-step (a) should be substituted for t_7 .

- (e) check the result obtained based on the check plot displayed; in case of discrepancy, determine and eliminate its cause;

- (f) after validating the result, insert the check plot in the appropriate space provided in Part 8 of the report.
10. Repeat steps 6 to 9 for the gate resistance of about 220Ω .

Result recapitulation

11. Include the parameters determined until now, together with the gate resistor values R_G measured, in appropriate tables in Part 4 of the report.
12. Calculate and enter in the final row of each table the rate of decrease $q_{\text{decr(LH)}}$ defined as in step 4.2/13. Show values with an accuracy of two significant digits.

Analysis of time-related parameters

13. Complete Part 4 of the report.

Current tail

14. Fill in Part 5 of the report.

Analysis of energy-related parameters

15. Fill in Part 6 of the report.

4.4. IGBT compared to MOSFET

1. Fill in Part 7 of the report.

5. Required Knowledge

5.1. Prerequisites

- Voltage and current waveforms during IGBT switching (Fig. 3; Ref. B)
- Physical and technical definitions of IGBT time-related and energy-related dynamic parameters (Figs. 3 and 4; Ref. B [21])
- Physical and technical definitions of MOSFET time-related and energy-related dynamic parameters (Manual 3P, Section 2.2 and Ref. C; Manual 6P, Section 2.2)

5.2. Test scope

1. Insulated Gate Bipolar Transistor: symbol, NPT (symmetric) N-channel IGBT cell cross-section, control and main (power) terminals. Two-element equivalent electrical schematics and their location within the semiconductor structure. (Ref. A)
2. IGBT static output characteristic. Operation in the diode region: 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. (Ref. A)
3. Voltage, current and instantaneous collector power waveforms during IGBT switching under 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-related and energy-related transistor parameters. (Ref. B; report)
4. Technical definitions of MOSFET and IGBT time-related and energy-related dynamic parameters (without specific thresholds). (Fig. 4; Ref. B [21]; Manual 3P, Section 2.2; Manual 6P, Section 2.2; report)

5. Gate resistance effect on the particular MOSFET and IGBT time-related dynamic parameters; explanation using the input capacitance-based control circuit model. Gate resistance effect on current tail parameters (magnitude, duration, energy), relation to physical principles of operation. Effect of time-related parameters on energy-related ones and its explanation.
(Manual 3P, Refs. C and D; Manual 6P, Section 2.2; report)
6. Differences between the MOSFET and the IGBT in respect of voltage and current waveforms during turn-on and during turn-off as well as of the influence the control circuit (the gate resistance) has on time-related and energy-related dynamic parameters. Relation to differences in physical bases of operation.
(Ref. B; Manual 3P, Ref. C; report)

In the case of report contents, only the qualitative aspect (mutual relationships and the character of variations) is to be considered while the quantitative one (specific numerical values) can be ignored.

6. References

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