



POWER DEVICES AND SYSTEMS LABORATORY

Exercise 6

Safe Operation of Semiconductor Devices Voltage and Current Ratings Heat Dissipation and Cooling

Indicatory work plan

Part	30'	45'	1 ^h	1 ^h 15'	1 ^h 30'	After Class
A	4.2/1-7	4.2/8-10	4.3/1-6		4.3/7-9	4.3/10 4.4 6.1
B	5.1/1-11	5.1/12-21	5.2	5.3/1-5	5.3/6-11	6.2
A&B						6.3 6.4

To be executed before class: 4.2/5

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Exercise Introduction

1. Exercise Aim and Plan

The aim of this exercise is to introduce the problem of safe operation of power semiconductor devices. Two aspects will be analysed: the voltage-related and the temperature-related one. The current limitation of a semiconductor device is strictly connected with the latter.

The above questions will be analysed based on a specific device example—the MOSFET. Its operation is relatively simple so it will not be necessary to consider details of secondary phenomena.

Nevertheless, principal guidelines and design techniques as well as simulation and measurement results remain valid for any other power semiconductor device (transistor, diode or thyristor). It specially concerns the heat flow system model and its computational applications. On the other hand, particular formulae for power loss in the device as well as Safe Operating Area plots may differ. Some aspects of safe operation will have high importance for some devices while they will be negligible for others. This results from different conduction, switching and breakdown mechanisms. However, the outline design methodology stays invariable.

Ensuring the safe operation of a device is a task of the circuit designer. This is why the present exercise includes design tasks. It will be possible to practise transistor selection for a given circuit. Then, using computer-aided and manual computation, a simple cooling system, restricted to a small heat sink, will be designed. In a second part of the exercise, the effect of this heat sink will be tested experimentally. It will also be possible to investigate a simple overvoltage protection for the transistor's main circuit.

Simulations carried out, apart from their design-related aspect, will enable to analyse the contribution of the different components (coming from the 4 semiconductor switch operating states) to the total power loss in the switch. The effect of frequency will also be investigated.

2. Thermal Phenomena in Semiconductor Devices

2.1. Recommended reading

Ref.	Textbook	Excerpt	Equivalent in the Polish Manual	Complementary Reading	Complements in this Manual
A	Moh	29-1, 29-2, 29-2-1, 29-2-2, 29-3, 29-4, 29-4-1, 29-4-2	2.1, 2.2, 3.2.c, 3.3.a,c, 3.4	[14] 7.1.1 (The power dissipation limit, Continuous power dissipation, Pulse power operation, Short pulse duration, Long pulse duration, Periodic rectangular pulse), 7.1.2 (Heat flow path, Thermal resistance calculations, Continuous operation, Intermittent operation) [16] 5	
B	Ben	2.1.4	2.3.a–d		

3. VDMOS Safe Operation

3.1. Recommended reading

Ref.	Textbook	Excerpt	Equivalent in the Polish Manual	Complementary Reading	Complements in this Manual
C*	Ben	10.4	2.3.e–f, 3.2, 3.3.b, 3.4.b, 3.5.a–c	[14] 1.2.1 (The Safe Operating Area), 1.2.7 (Introduction, Failure mechanism of a non-rugged Power MOS, Definition of ruggedness), 1.2.9 (Quick reference data, Limiting values, Static characteristics, Safe Operating Area, Calculating currents), [15] 1–4 [16] 1–3	
D**	Ben	6.2.4, 6.4, Fig. 6.6	2.3.e–f, 3.1.a, 3.2.d	[14] 2.1.2 (Safe Operating Area), Fig. 10	
E	Moh	27-4	3.5.d	[17] 4	

* Ref. C is found in the document already published as Refs. ABCD for Manual 3^A; the Fig. 3.19 referenced there is found in Ref. H for Manual 0.

** Ref. D is found in the document already published as Refs. AB for Manual 5^A.

4. Design and Simulations

4.1. DC voltage chopper

Circuit topology and operation

Fig. 1 presents the schematic of the circuit to be analysed. It is a low-side switch—the simplest power switched-mode circuit topology, which can be used to realise the simplest electronic power converter, the DC voltage chopper.

The term “low-side” indicates the placement of the semiconductor switch (transistor T in Fig. 1) with respect to the load (resistor R_L in Fig. 1). In this circuit, the switch is situated on the side of the lower potential (negative terminal) of the power supply U_{DD} , so “lower” than the load. In the opposite case, when the switch is located “higher” than the load, i.e., on the side of the higher potential (positive terminal) of the power supply U_{DD} , we speak about a high-side switch.

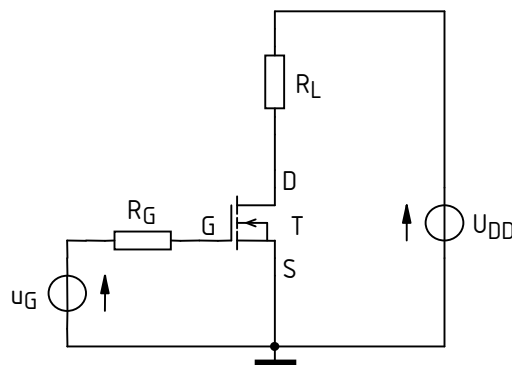


Fig. 1. The schematic of the low-side switch circuit to be used in simulations

The name “chopper” describes the function fulfilled by the considered circuit; it is periodic chopping of supply voltage as it is applied to the receiver (load). Transistor’s state changes according to the drive pulse wave u_g :

- (1) when the transistor is on, the resistance between its source and drain is low, which enables current flow in the power loop. If we assume that the transistor is an ideal switch, it represents a short-circuit, so full supply voltage U_{DD} is applied to the receiver R_L (see Fig. 2a);
- (2) when the transistor is off, the resistance between its source and drain is high, which disables current flow in the power loop. If we assume that the transistor is an ideal switch, it represents a gap; as no current is flowing, the voltage across the R_L resistor is zero (see Fig. 2b).

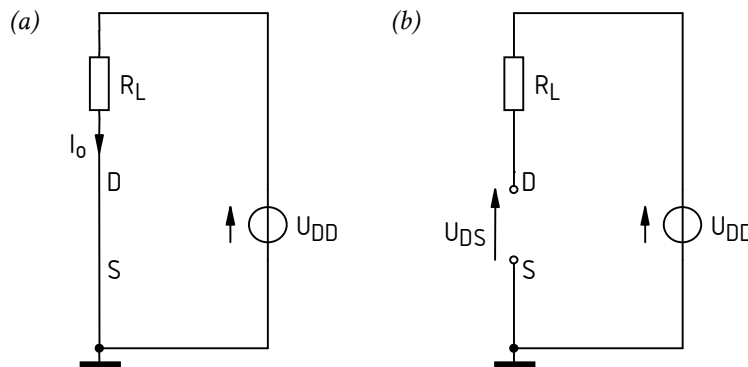


Fig. 2. Power loop of the chopper circuit for an ideal semiconductor switch: (a) in the on-state; (b) in the off-state

Any change in the duty cycle D of the u_g waveform results in a change of length of the time interval during which the transistor is on. This way, the rms value of the voltage applied to the receiver can be regulated, and so can be the receiver’s (or output) average power.

The considered circuit realizes the function of lowering the output voltage average value, or its DC component (see Manual 3^B, Ref. B). It therefore belongs to the DC/DC converters group. However, it is so simple that it does not contain any output filter (as you can easily state, it is the circuit analysed in Exercise 3^B before capacitor and choke are inserted). Therefore, the output voltage (across the receiver R_L) is a square wave instead of a constant one (even roughly).

Parameters of the circuit under investigation

In the circuit investigated in this exercise, component parameters are as follows:

- power loop supply voltage $U_{DD} = 24$ V,
- load resistance $R_L = 10$ Ω ,
- gate resistance $R_G = 100$ Ω ,
- switching frequency $f_s = 10$ kHz (although it will vary during a first part of the exercise),
- control waveform duty cycle $D = 0.5$.

The transistor will be selected during the exercise. For simplicity, we assume that the available components include only:

- transistors manufactured by International Rectifier from the standard series, where the alphabetic part of designations is IRF (meaning not IRFB, nor IRFZ);
- heat sinks fitting only the most popular package (for the considered power range and through-hole mount), which is the TO-220 or TO-220AB, which dictates the package type of the transistor.

The control waveform source u_G should model a real drive circuit. Its output component block is an integrated gate driver, IR2117, whose datasheet is attached to this manual.

4.2. Completion of component definitions

Schematic, sources and passive components

1. In the *MicroSim* environment create a new project in a way indicated in the manual available at the experimental stand.
2. Copy the file *lacznik_dolny.sch*, which contains the schematic corresponding to the circuit of Fig. 1, to the newly created project folder.
3. Open the schematic in the *Schematics* program (see manual available at the experimental stand, the case of work with an existing project).
4. Modify the names of all circuit components by changing “??” to your group number (e.g., UG99)

Submitting results with incorrect component names will be considered as cheating.

5. From the web page, obtain the initial value $f_{s,ini}$ for the switching frequency.
6. Based on the data given in Section 4.1, complete the schematic with component parameters:
 - (a) double-clicking on the “?” symbols near appropriate components, enter the values of U_{DD} , R_L and R_G ;
 - (b) double-click the u_G source symbol and enter the parameters of the control waveform (parameter names are abbreviated in the simulator):

The MicroSim environment enables introducing numbers with unit prefixes. For circuit description (i.a. in Schematic) these are: f, p, n, u (meaning μ), m, k, Meg (meaning M), G, and are case insensitive. In the case of Probe, they are: f, p, n, u, m, k, M, G, and are case sensitive. Results will be presented in Probe in this form, too.

The simulators of the SPICE family have their own circuit description language where the dot is the decimal sign (so not the comma). This convention should therefore be followed when entering numbers in the MicroSim package.

- period T_p , which can be calculated from the known frequency $f_{s,ini}$;
- pulse width t_p , which can be calculated from the known frequency $f_{s,ini}$ and duty cycle D ;
- rise time t_r taken from the datasheet of the gate driver (use the typical value—*typ* column);
- fall time t_f taken from the datasheet of the gate driver (as above);
- signal range from 0 V – low level $V1$ (a typical value used to turn off the transistor) to 15 V – high level $V2$ (a typical maximum allowed gate-source voltage for MOSFETs used in the considered power range, with an appropriate safety margin).

Transistor selection

7. Determine the main transistor parameters required for safe operation in the considered circuit:
 - (a) rated current I_D :
 - estimate (by calculation) the load current I_o , i.e. the current that will flow in the power loop after the transistor is turned on (assume that the transistor is an ideal switch, see Fig. 2);
 - assume that transistor’s rated current I_D for the case temperature of 100 °C should be greater than the above-calculated load current I_o with a safety margin of 20%;
 - express the minimum rated current $I_{D,min}$ necessary according to the above assumption, as a number;
 - (b) rated voltage U_{DSS} :

- deduce what drain-source voltage $U_{DS(off)}$ will appear across the transistor in its static off-state (still assuming that this switch is ideal, see Fig. 2);
 - based on the above-determined value of $U_{DS(off)}$, calculate the minimum necessary rated voltage $U_{DSS,min}$ according to the rule-of-thumb saying that the voltage rating should be by at least 50% greater than the maximum voltage that may appear across this transistor while in the off-state.
8. Look up the appropriate transistor using the internet catalogue of Vishay company, proceeding exactly in the following way, the order of operations included:
- (a) in a web browser, open the page www.vishay.com;
 - (b) choose subsequently:
 - MOSFET transistors – *MOSFETs* (not the *Automotive*, *Hi-Rel Military* or *Medical* sub-groups),
 - single transistor configuration – *Single*,
 - package according to the assumption given in Section 4.1 (exactly the designation given);
 - (c) using the filter function (funnel symbol) in the *Channel* column, choose the devices with the appropriate channel type, i.e. N or P, according to the transistor symbol appearing in Fig. 1;
 - (d) using the sort function (arrows symbol), sort the results by the rated current $I_{D(max)}$;
 - (e) choose (in your mind; do not click on anything) a transistor:
 - from within transistors having rated currents I_D close to, but not smaller than, the minimum one $I_{D,min}$ determined in step 7(a),
 - having a rated voltage U_{DSS} (V_{DS}) closest possible to (which does not mean equal nor very close), but not lower than, the value determined in step 7(b),
 - whose designation conforms to the assumption given in Section 4.1;
 - (f) in order to limit the number of current/voltage combinations, narrow the list to rated voltages within the range from the voltage determined in step 7(b) to the one of the transistor chosen in sub-step (e)—click the V_{DS} column filter icon and, while keeping the *Ctrl* key pressed, select all the values falling in the given range;
 - (g) in a new browser tab open the page for the selected transistor by right-clicking its designation in the first row of the table and choosing *Open in new tab*;
- Do not lose the list of transistors presently obtained by opening transistor pages in current browser tab as this would considerably increase the execution time of the present step by making it necessary to re-create this list each time from scratch.**
- (h) open the datasheet for the chosen transistor;
 - (i) from the datasheet, read the maximum admissible drain current I_D ; according to the assumption given in step 7(a), the value for the case temperature $T_c = 100\text{ °C}$ is to be considered;
 - (j) if the value read out in sub-step (i) is greater than the minimum one determined in step 7(a), proceed to step 9;
- otherwise:
- close the data sheet;
 - proceed (in your mind) to the next transistor in the result list (in the previous browser tab), considering the assumption concerning its designation (Section 4.1),
 - go back to sub-step (g).
9. Save the copy of the datasheet in your folder, as it will be needed later on.
10. Place the selected transistor in the circuit, using the model for the junction temperature 25 °C and name it according to the guideline given in step 4.

The models for different temperatures are indicated by the suffix “_xC” added to their file names, where x is the temperature value in degrees Celsius. We are choosing 25 °C because initially we will be examining the influence of other parameters, so the omission of transistor heating will simplify analysis of the results.

4.3. The effect of the switching frequency on energy loss

Starting the simulation

To perform the operations below you will need the MicroSim and Probe manuals available at the laboratory stand.

1. Define the simulation parameters such that:
 - the transient simulation is enabled and all other simulations are disabled;
 - the analysis stop time allows to observe the periodic operation of the circuit with the frequency calculated in step 4.2/5.

The basic parameters of the transient analysis are as follows:

- *Final Time* – time when the analysis finishes.
 - *Print Step* – the step of dumping the results to the text file should be lower than *Final Time* (we are not using the test file, so the step should be as large as possible to speed up the simulation),
 - *No-Print Delay* – time at which the storage of results starts (it is not necessary fill it in, the default is 0),
 - *Step Ceiling* – the maximum analysis step, the lower it is, the more accurate the results are, but the simulation takes more time (if not specified, the simulator will choose the step automatically according to the speed of variation of different quantities in the circuit).
2. Start the simulation and plot the transistor drain current. If it turns out, that the final simulation time has been chosen incorrectly (see step 1), change the settings and re-run the simulation.

While using the *Add Trace* function is used in the Probe program, do not plot any waveforms from the subcircuit being the transistor model! They can be recognized by the **letter X in the name**. They can be hidden in the *Add Trace* window by unchecking the option *Subcircuit Nodes*. Between them are found the waveforms denoted ID, IG etc., which can be misleading; they are currents of some low-power MOSFET, being just single components of the model, and should not be confused with the currents at the terminals of the power MOSFET.

The above problem can also manifest if current probes are used in Schematics. In this case, it is impossible to apply them to any of the MOSFET terminals. This problem is described in the available manual for the MicroSim package.

From the topology of the power circuit and Kirchhoff's voltage law one can infer that the transistor drain current should be positive. If the sign of displayed current is negative, it is a result of connection of the virtual probe in the *Schematics* program to the pin whose current is by convention directed in the opposite direction than the real current in the circuit. The user does not have any influence on the choice of voltage and current directions by the simulator. In such a case, you should correct the waveform by moving the current probe to the opposite terminal of the component or by adding a minus sign ("-") in the waveform definition (in *Probe*; double-click the definition under the plot).

3. Using an additional Y-axis (*Plot* ▶ *Add Y Axis* from the menu), at the same graph plot the drain current, drain-source voltage u_{DS} , the drive voltage source u_{GG} and the gate-source voltage u_{GS} . Find out, if the observed waveforms are characteristic for the operation of transistor as a switch, and if its drive and switching are performed with the frequency and duty cycle given above. If not, check if the circuit parameters are correct and transistor model has been chosen correctly.

Instantaneous power loss in the transistor

4. Over the drain current i_D plot add a separate graph (*Plot* ▶ *Add Plot* from the menu) and plot the instantaneous power loss p_D in the transistor's drain circuit (enter the appropriate mathematical formula; see e.g. Manual 3^A, Section 3.2).

If the formula involves a combination of the multiplication sign and the minus sign, the expression including the minus sign must be put inside parentheses. Otherwise, a calculation error can arise which will make the application close.

5. Obtain an appropriate result accuracy:

- (a) zoom in the time scale so as to observe the turn-on state of the transistor (see Fig. 3);

In this exercise, waveforms should be zoomed using the *View Area* button, not the *View In* one. This is due to the fact that waveforms will have to be zoomed primarily in the time axis and much less so in the Y-axis, whereas *View In* causes both axes to be scaled by the same ratio.

The *View Area* button is best to be used in the current and voltage sub-plot (and not in the power and energy sub-plot). This is because thanks to it, power and energy scales will be automatically adjusted to their respective ranges within the zoomed time interval.

- (b) display data points clicking the *Mark Data Points* button or choosing *Tools* ▶ *Options* from the menu and checking the *Mark Data Points* option;
- (c) state whether the instantaneous power waveform is represented accurately, i.e. multiple, not just few, data points are shown at every stage of turn-on and the curve appears as a smooth (not broken) line; otherwise, in the Analysis Setup dialogue in Schematics, enter a maximum analysis step (distance between data points; see step 1) that will enable obtaining sufficiently high an accuracy of the instantaneous power waveform (note that, on the other hand, too small a step will make the simulation time unnecessarily long);
- (d) turn-off the *Mark Data Points* option.
6. Using cursors (see the *Probe* software manual), read out peak instantaneous power losses $p_{D(pk)}$ in the different 4 operating states (turn-on, conduction, turn-off, blocking), where (cf. Fig. 3):
- the first two switching periods should be disregarded as it is possible that the state of the simulated circuit is not steady yet;
 - the operating state should be determined based on the observation of the drain current i_D ;
 - in the static states by definition the power does not change, so the peak value is identical to the constant value of power in these states;
 - because of the small variation of the power in static states you can assume, for example, that the readout will be performed always in the middle of duration time of given state, where one can be sure, that the state of the transistor has stabilized.

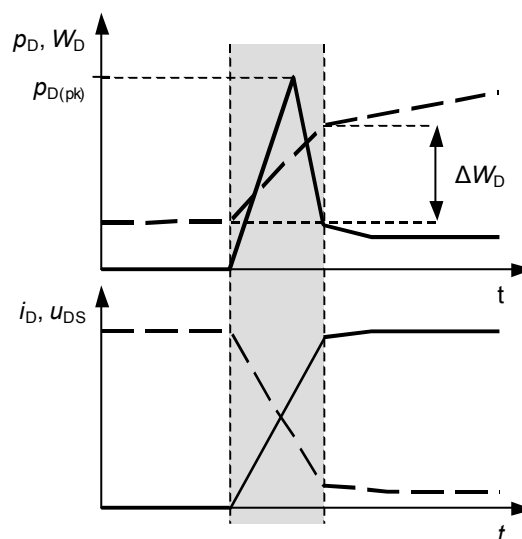


Fig. 3. Readout example of peak instantaneous power loss $p_{D(pk)}$ and energy dissipation ΔW_D within one operating state—turn-on state (simplified waveforms)

Energy dissipation in the transistor

7. Add another Y axis to the plot of instantaneous power and plot the energy dissipated in the transistor's drain circuit $W_D(t)$. For this purpose derive a mathematical formula corresponding to the equation (see Manual 3^A, Ref. D)

$$W_D = \int p_D(t) dt \quad (4.1)$$

The *Probe* program has the $S()$ function, which computes the integral of any waveform (or combination of waveforms) from the time 0 to the time instant t :

$$S(y(t)) = f(t) = \int_0^t y(\tau) d\tau \quad (4.2)$$

where τ is the auxiliary integration variable, which for every point t "sweeps" the time axis in the range from 0 to t .

From the above, the waveform $W_D(t)$ in a given time point t represents the total energy dissipated in the drain circuit from the instant $t_0 = 0$ up to the given instant t :

$$W_D(t) = S(p_D(t)) = \int_0^t p_D(\tau) d\tau \quad (4.3)$$

The $W_D(t)$ must be a monotonically increasing function, as the transistor is a purely dissipative component, i.e. it does not store the energy, but only dissipates it.

Obviously, the difference in $W_D(t)$ value between two time instants ΔW_D (see Fig. 3) represents the amount of energy dissipated in this transistor during this time period. If these points correspond to the beginning and the end of given state of the transistor, the ΔW_D increment will correspond to the energy W_D dissipated in the transistor in this state.

8. Save the waveform with at least one full switching period of the transistor visible: choose *Tools* ▶ *Copy to Clipboard* from the menu and paste to a text document or to a graphics editor and save the file.
9. Using the cursors, from the waveform $W_D(t)$ read the energy W_D dissipated in all 4 operating states during one (the same) switching period (see Fig. 3), where:
- the first two switching periods should be disregarded for the reasons stated earlier;
 - dynamic states limits should be determined based on the instantaneous power waveform;
 - the beginning of the turn-on state and the end of the turn-off state are clearly visible;
 - the end of the turn-on state and the beginning of the turn-off state should be determined based on the criterion of the instantaneous power reaching 100% of its steady on-state value as read out in step 6.

Save the waveforms during turn-on and turn-off with the magnified time scale (same scale if possible, two separate pictures).

Simulation for different operating conditions

10. Repeat steps 1–9 for the following control waveform frequencies of:

(a) $f_{s,ini} \times 5$,

(b) $* f_{s,ini} / 5$.

For this purpose, the parameters of the u_g source must be modified as appropriate [see step 4.1/6(b)]. All the other circuit parameters, including the control waveform duty cycle D , should remain unchanged.

4.4. Design of the transistor cooling system

1. Replace the transistor model (insert a new component) for the one corresponding to the maximum allowed temperature 150 °C. Restore the previous name of the component.

For the analysis of the operation safety assume the worst case from the thermal point of view. This is the case of the maximum temperature value, not only because of the high temperature, but also because the drain source resistance in the on-state $R_{DS(on)}$ will be maximal, making the static power dissipation also maximal (see Ref. D [14] and Manual 3^A, Ref. A). Therefore, if we ensure the safe operation of the transistor in these conditions, it will be safe in any other.

2. Change the parameters of the driving source so that the switching frequency f_s becomes 10 kHz. The duty cycle D should still be equal 0.5. Adjust the simulation parameters as appropriate (see step 4.3/1) and re-simulate.
3. Plot the drain current i_D and the instantaneous drain circuit power loss p_D . Add a moving average waveform of the power loss p_D ; the AVG function is provided for this purpose, which is defined as

$$\text{AVG}(y(t)) = f(t) = \frac{1}{t} \int_0^t y(\tau) d\tau \quad (4.4)$$

From the moving average plot obtained, read the average power loss $P_{D(av)}$ taking into account that *average power* as an electrical quantity is defined (see Manual 0, Ref. C) as the average value of the instantaneous power over its period, which is the switching period T_s here.

It follows from the average power and AVG function definitions cited above that the reading from the AVG function waveform should be made at a time point t that corresponds to the switching period T_s . However, for the reasons given earlier, the first two switching periods should still be disregarded. After this time, the waveform can be assumed to be ideally repetitive, thus the average value will be identical after each next period. Eventually, the read-out should be made at any time being an integer multiple of the switching period T_s greater than two.

4. Save the graph.
5. Using the simplified Fourier's law of heat conduction for pulsed operation ([16], Section 5), based on the datasheet of the transistor, calculate the maximum admissible power loss $P_{D(max)}$ without a heat sink. Assume an ambient temperature $T_a = 25$ °C, which corresponds to the experiment conditions in the second part of this exercise.
6. By comparing the power losses: the one predicted through simulation (step 3) and the calculated maximum admissible one (step 5), determine whether the operating conditions of the device are safe from the thermal point of view.
7. If the operating conditions of the transistor without a heat sink are not safe, calculate the maximum thermal resistance $R_{th(s-a)}$ which an additional heat sink should have not to exceed the maximum junction temperature (still in the same electrical operating conditions). Still use the approximate Fourier law formula as in step 5. The necessary thermal resistances of the transistor should be read from the datasheet.

5. Measurements

5.1. Preparation of the measurement circuit

Circuit description

The schematic of the experimental circuit is presented in Fig. 4. Marked points are connected to the **sockets in the front panel**. Voltage measurements are done using voltage probes appropriately connected to banana sockets labelled as v_S , v_G and v_D . For this purpose, banana connectors are available that enable attaching a probe. These connectors may be freely moved depending on current measurement needs.

A blue screw terminal block allows to insert the transistor T into the circuit. The R_L and D_0 components are connected through sockets on the panel, according to Fig. 4.

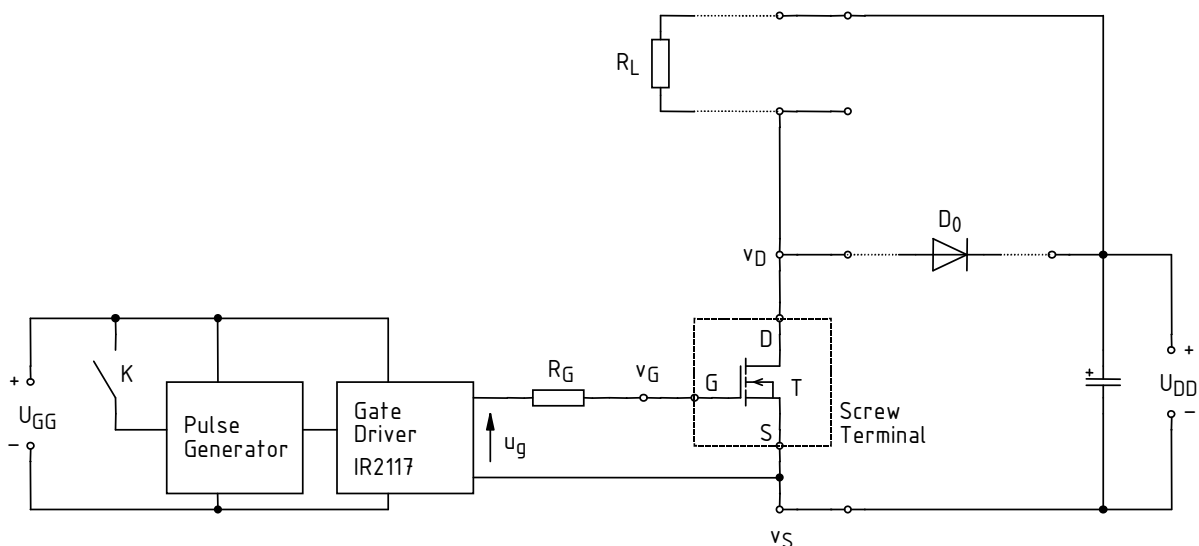


Fig. 4. Schematic of the experimental circuit

Transistor is driven from a built-in pulse wave generator (see Manual 3^B, Section 2.2) with parameters as considered at the end of the first part of this exercise, i.e. switching frequency $f_s = 10$ kHz and duty cycle $D = 0.5$. The pulse wave u_g is applied to the transistor's gate through the IR2117 gate driver and a 100Ω gate resistor R_G . The amplitude of this waveform is approximately equal to the supply voltage of the control circuit which should be $U_{GG} = 15$ V. Thus, parameters are as in the first part of this exercise (cf. Section 4.1).

The generator is started by pressing a button on the panel (switch K in Fig. 4): the green one (to switch on for the time the button is kept pressed) or the red one (to switch on permanently).

Generator's operation is indicated by a yellow LED. The generator may only be switched on permanently when you are so advised in this manual. Apart from those moments, the generator should be switched on temporarily so as not to cause transistor overheating.

As in the first part of the exercise, there is a **load** in the power circuit consisting of the resistor $R_L = 10 \Omega$ with the maximum allowed power 50 W, supplied from the DC voltage source $U_{DD} = 24 \text{ V}$.

For measurements and recording of voltage waveforms, an oscilloscope with OpenChoice Desktop software is used (see the manual available at the stand).

For temperature measurements the multimeter with the **contact temperature probe** is used. The basic element of the probe is the thermocouple located at the tip of the probe. Only the contact of the thermocouple enables the temperature measurement, other parts of the probe should not touch the measured objects. For data recording, the Metex ScopeView program is used, its usage will be described elsewhere in this instruction.

Warning!

During this exercise the transistor case and load resistor can be very hot, which can cause skin burns and melting of the isolation of the cables! During this exercise make sure that no cables (including the scope probe cables) are touching the transistor nor the load resistor at any time.

Circuit configuration

A block diagram of the measurement set-up is presented in Fig. 5. It should be assembled and configured in the way described below.

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

1. Turn on the computer. After logon is completed, turn on the oscilloscope and configure its connection to the computer strictly following the procedure described in the manual available at the laboratory stand.
2. Turn off and disconnect from the circuit the 3-section power supply, then switch it into the mode of independent operation of the adjustable sections (two buttons in the middle of the front panel).
3. Using short wires, connect the „-” terminals of both adjustable sections of the power supply to neighbouring ground (GND) terminals.
4. Connect the voltage from one adjustable supply section to the supply sockets of the control circuit U_{GG} , and from the other - to the power circuit supply sockets U_{DD} .

To avoid damaging the transistor's gate by an electrostatic discharge, perform all the manipulations with it after grounding yourself, e.g. by touching the ground of an oscilloscope input! Do not touch the transistor's leads; only grab it by its plastic case or its metal base (heat sink).

5. Mount in the blue screw terminal block the transistor selected in the first part of the exercise (if already performed) or the one indicated by the teacher, applying the following:
 - to determine terminal block pin arrangement, compare Fig. 4 to the connection drawing on the circuit's panel;
 - transistor terminal arrangement can be checked in its data sheet saved during the first part of this exercise (if already carried out) or on manufacturer's web site www.vishay.com, by entering the designation read out from the package (IRF...) in the *Search Part Number* field;
 - if the transistor has a heat sink attached, detach it.
6. Connect the load resistor R_L with the parameters given above. If the clamping diode D_0 is found in the circuit, disconnect it.
7. Connect the voltage probe to the channel 1 of the oscilloscope. Choose the attenuation 10:1 (10x) using the switch on the probe (if present).

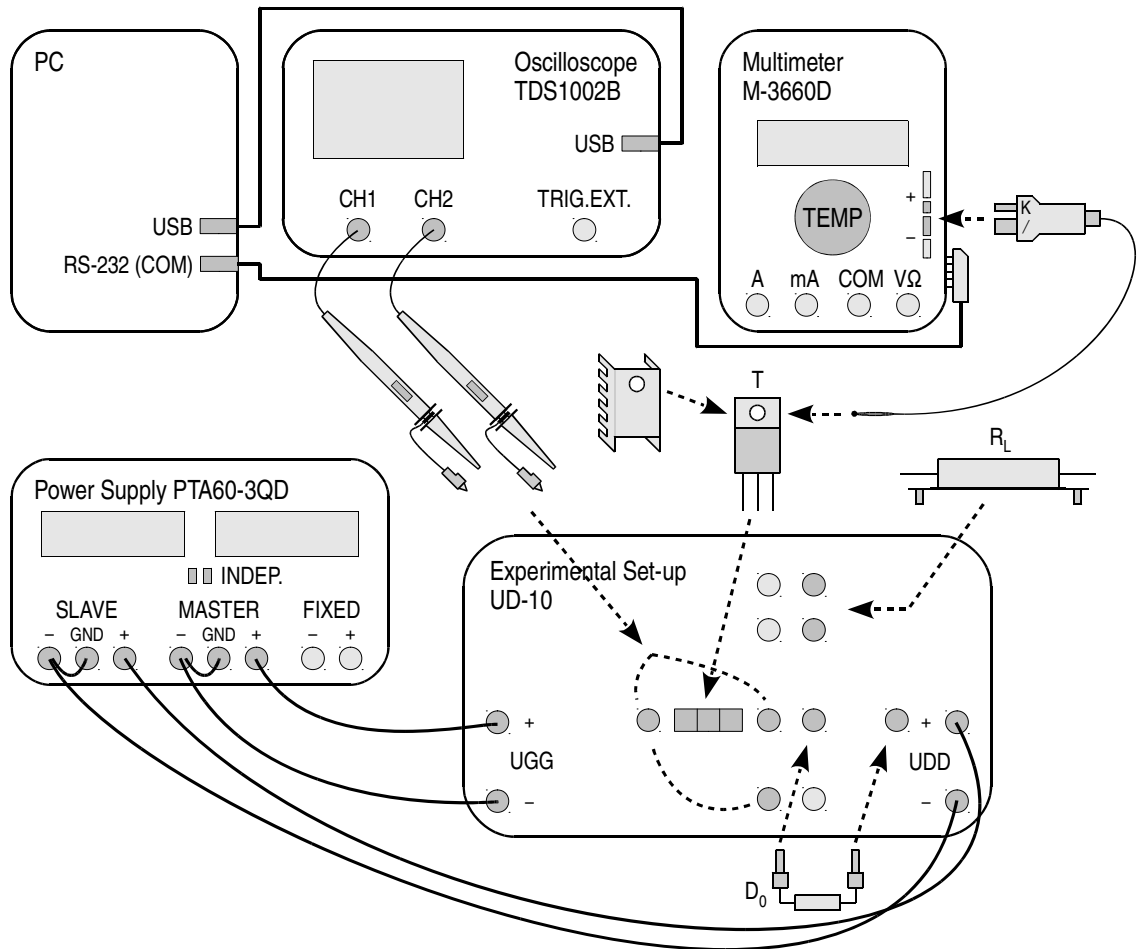


Fig. 5. Block diagram of the measurement set-up

8. Connect the probe to the terminals at the circuit panel so that it measures the u_{GS} transistor voltage.

Before switching on the power supply, the connections must be checked by the teacher!

During and after execution of the next step, the current consumed by the circuit in stand-by (generator turned off) should not exceed 10–20 mA – if other values are observed, turn off the power supply and ask the teacher!

During voltage setting, pay attention not to ever exceed the value of 18 V as this might damage integrated circuits.

9. Turn on the power of the control circuit:
 - (a) turn the knobs *Voltage* and *Current* of both sections of the power supply to zero (extreme counterclockwise position);
 - (b) turn on the power supply;
 - (c) slightly increase the current limit of the section supplying the control circuit (the *Current* knob), so that the red current limit signal turns off;
 - (d) set the U_{GG} voltage to the value given above. If during this operation the current limit turns on, first turn the Voltage knob to the left, next increase the current limit and only then increase the voltage again.
10. Using the oscilloscope communication software, load initial settings into the oscilloscope:
 - proceed to the tab *Get & Send Settings*;
 - press *Open* and read the file *ustawienia_tds1002b.set*;
 - press *Send Settings*;

- go back to the tab *Screen Capture*.

- Using *Ch1/2 Menu* buttons on the oscilloscope, display the Channel 1 waveform and hide the Channel 2 one.

Ch x Menu buttons (where x is channel number) toggle display and hide the waveform from a given oscilloscope channel. When a given waveform is displayed, this is indicated by an arrow left of the graticule showing the zero level as well as by the channel symbol “CH x ” under the graticule.

Supplying the circuit

- Permanently turn on the pulse generator. The yellow LED indicator on the circuit panel should light.
- Set the time base (knob *Sec/Div*) and optionally the position of the waveform on the screen (knob *Horizontal Position*) such that 2-4 periods of waveform u_{GS} are visible on the screen. The vertical scale of the oscilloscope channel (*Volts/Div* knob) and the position on the screen (knob *Vertical Position*) can be set in any way making it possible to observe the waveform.
- Download the waveform to the computer – click *Get Screen*. Save the picture with the button *Save As* (confirm with the mouse click, using of the Enter key will reopen the dialog box).
- Switch on the normal trigger mode of the oscilloscope – button *Trig Menu, Mode: Norm*.
- Turn off the pulse generator.
- Supply the power circuit:

During and after execution of the next step, the current consumed by the should not exceed 10–20 mA—if other values are observed, turn off the power supply and ask the teacher!

During and after execution of the next step, the red LED indicator on the circuit panel should be lit. If not, turn off the power supply and ask the teacher for help.

- slightly increase the current limit of the section supplying the power circuit (the *Current* knob), such that the red current limit signal turns off and set the U_{DD} voltage to the value given above. If during this operation the current limit turns on, first turn the *Voltage* knob to the left, increase the current limit and then increase the voltage again;
- increase the current limit of the section supplying the power circuit to the maximum;

Sub-steps (c)–(d) should be performed quickly, such that the time of the generator operation does not exceed 20–30 s, otherwise the transistor will be overheated and damaged! If necessary, turn off the generator for at least as long as it was turned on and only then turn it on again.

After execution of the following sub-step (but before executing the next one), the readout from the current meter in the power supply should be close to the value of $D \cdot U_{DD} / R_L$; if you anything else is observed, turn off the power supply and ask the instructor for help!

- turn on the pulse generator; if the current limiter of the section supplying the control circuit activates, increase slightly the current limit of this section until the red signal turns off;
 - turn off the pulse generator.
- Connect the voltage probe to the channel 2 of the oscilloscope. Choose the attenuation 10:1 (10x) using the switch on the probe.

The grounds of the voltage probes are connected to each other and connected to the mains protective ground inside the oscilloscope; therefore they must be connected to the same potential. Other connection may result in current flow through the oscilloscope and damage of its input circuitry! In case of doubts, ask the teacher before connecting the probe.

- Connect the probe to the terminals on the circuit panel so that it measures the u_{DS} voltage of the transistor. If only one of the probes has a ground connector available, it should be connected to

- the probe measuring the u_{DS} voltage. Using the *Ch2 Menu* button display the channel 2 waveform.
20. Turning on the generator for a short time, adjust on the oscilloscope:
 - (a) channel gain (*Volts/Div*) and vertical waveform position (*Vertical Position*) so that both waveforms are well visible on the screen from their zero levels to maximum values including the overshoots and can be distinguished one from another;
 - (b) time base (*Sec/Div*) and trigger event position (*Horizontal Position*) so that from 1 to 2 periods of the waveforms are visible.
 21. Download the screen image to the *OpenChoice Desktop* program by pressing *Get Screen* and save to the graphics file.

5.2. Voltage safety

The following steps should be performed by turning on the generator for no longer than 20 to 30 s and using the same intervals between the subsequent measurements! Analyse and download the waveforms to the computer while the generator is turned off! (Waveforms should stay on the oscilloscope screen after generator is switched off.)

1. * Examine the transistor operating conditions in the current circuit:
 - (a) based on the waveforms on the oscilloscope determine, in which of the four states of operation (static and dynamic) the voltage u_{DS} reaches its maximum value;
 - (b) hide the u_{GS} waveform (but do not detach this channel's probe from the oscilloscope nor from the circuit)—*Ch1 Menu* button;
 - (c) observe the operating state selected in sub-step (a) with the maximal magnification of the u_{DS} waveform – appropriately choose the trigger slope (*Trig Menu*), time base (*Sec/Div*), waveform position (*Horizontal Position*, *Vertical Position*), vertical scale (*Volts/Div*);
 - (d) download the waveform to the computer and save it.
2. * Check the possibilities of improvement of the operating conditions using the clamping diode:
 - (a) turn off the power supply;
 - (b) connect the clamping diode D_0 between the transistor drain and the positive terminal of the power supply (filtering capacitor at the U_{DD} input) according to Fig. 4 (be careful not to tear the diode terminals away from the plugs); pay attention to the diode orientation—the cathode is indicated by the grey strip on the package;

Connecting the diode in the wrong direction can damage the transistor! The teacher has to verify the connections before proceeding!

After the next step, the readout from the power supply current meter should be the same as before; if you observe something else, turn off the supply immediately and ask the instructor for help!

- (c) turn on the power supply;
- (d) repeat sub-steps 1(c)–(d).

5.3. Thermal safety

Within this paragraph, either all the optional steps marked with an asterisk should be done, either none of them.

Measurement set-up configuration

1. If the paragraph 5.2 has been omitted:
 - (a) turn off the power supply;
 - (b) connect the clamping diode D_0 between the transistor drain and the positive terminal of the power supply (filtering capacitor at the input U_{DD}) according to Fig. 4 (be careful not to tear the diode terminals away from the plugs); pay attention to the diode orientation - the cathode is indicated by the grey strip on the package;

Connecting the diode in the wrong direction can damage the transistor! The teacher has to verify the connections before proceeding!

After the next step, the readout from the power supply current meter should be the same as before; if you observe something else, turn off the supply immediately and ask the instructor for help!

- (c) turn on the power supply;
- (d) * hide the u_{GS} waveform on the oscilloscope (but do not detach this channel's probe from the oscilloscope nor from the circuit)—*Ch1 Menu* button.

The following step should be performed by turning on the generator for no longer than 20-30 s!

2. * Set on the oscilloscope:
 - a time base allowing observation of 1 to 2 switching periods;
 - channel gain and vertical waveform position allowing to observe with maximum zoom the full amplitude of u_{DS} voltage from zero to the steady value of U_{DD} (ignore the overshoots now);
 - to ease further data processing, it is best to adjust the vertical position of the waveform so as its zero level (indicated by an arrow with channel number left to the graticule) is found at an entire division—the exact zero position is indicated below the graticule while the *Vertical Position* knob is being used.

3. Configure the M-3660D (not any other) multimeter for temperature measurements:
 - (a) plug the yellow temperature probe into the appropriate multimeter socket, appropriately oriented according to markings on the probe's plug and on the meter's casing (see Fig. 5);

Do not force the plug in, as it may break the key forcing the appropriate orientation of the plug. With proper orientation, the “-” marking on the probe's plug and on the meter's casing should be located side by side.

- (b) switch the multimeter into the temperature measurement mode *Temp*;
- (c) connect the multimeter to the computer using the RS232 interface whose 5-pin socket can be found on the right side of the multimeter enclosure; a black cable with an adequate plug is available at the laboratory stand;
- (d) turn on the multimeter.

If the battery discharge indicator (a battery symbol) shows up on the meter's display, do not continue measurements but ask the teacher to replace the battery. Otherwise meter indications may become erroneous.

4. Set up and configure the connection of the multimeter to the computer:
 - (a) start the Metex ScopeView application (don't close the OpenChoice Desktop application);
 - (b) start the communication using the *Power* button;
 - (c) the multimeter's readout should appear in the application window and refresh periodically; if this does not happen:
 - check which port of the computer the multimeter is connected to,
 - click *Setup* and check if the settings are conforming to the reality and if the transmission speed (*Baud Rate*) is correctly set to 1200 baud;

After executing the following sub-step, don't close the Control Panel dialog window displayed!

- (d) click *Scope* and in the *Control Panel* window displayed:
 - uncheck *Auto Scale On*,
 - enter *Units/div*: 20,
 - enter *Offset*: 0,
 - leave *Trigger On* unchecked (or uncheck it if checked),
 - enter *Sample Every*: 1 sec,
 - enter *Sweep Mode*: Repetitive,
 - enter *Sweep Magnify*: Expand X1.

In step 5 one person should deal with the measurement circuit and the probe, the other one—the oscilloscope and the computer.

Recording the transistor heating process

5. Record the transistor heating curve (* and the transistor voltage waveform) under the current conditions:
 - (a) in the ScopeView program click *Record*, choose the location and name of the target file, accept;
 - (b) open the *Output* window by clicking *Scope*;

From this step on, if recording is interrupted before the planned measurement termination, or if the *Output* window is closed, then before starting recording again, return to step (a) and create a file with a different name. Otherwise, new results will not be written to the file.

- (c) make sure, that no cables are touching the transistor package not the load resistor;

Before performing the following sub-steps, read them entirely to the end.

- (d) touch the probe thermocouple (see remarks regarding temperature measurements given in paragraph 5.1) to the transistor's metal mounting base (so not to the plastic element of the case) so as to measure the package temperature T_c [see Fig. 6(a)];
- (e) start the recording in the ScopeView program - *Run* button;
- (f) turn on the pulse generator and immediately proceed to sub-step (g);
- (g) * download the u_{DS} waveform from the oscilloscope to the computer and save;
- (h) observe the thermometer readout and if the measured case temperature T_c reaches the value of ca. 130 °C (what in given conditions corresponds approximately the maximum allowed junction temperature T_j), immediately perform the following sub-steps in their very sequence;
- (i) * stop the u_{DS} waveform on the oscilloscope - *Run/Stop* button;

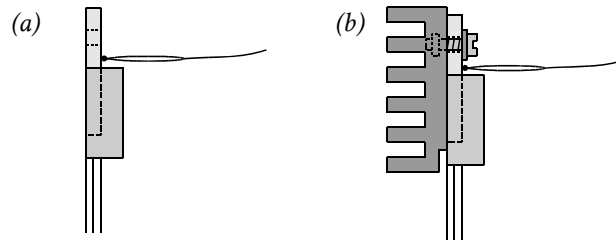


Fig. 6. Techniques for temperature measurement using the temperature probe and for attaching the heat sink to the transistor's case: (a) transistor without heat sink; (b) transistor with a heat sink

- (j) stop the data recording in the ScopeView program – *Stop* button;
 - (k) turn off the pulse generator;
 - (l) * download the u_{DS} waveform from the oscilloscope and save it;
 - (m) * unfreeze the oscilloscope display—*Run/Stop* button;
 - (n) check whether a file under the name given in sub-step (a) has been created and whether it contains correct measurement results, i.e. a large number of lines where in the first column, temperature values are found spreading from the room one to the last one observed, and in the fourth column, measurement times, in one-second increments, are found.
6. Attach the heat sink to the transistor:
 - (a) turn off the power supply;
 - (b) among the available heat sinks (see Table 1) choose the appropriate one according to the thermal resistance criterion according to the result obtained in the first part of the exercise (if already performed) or indicated by the teacher;
 - (c) write down the thermal resistance of the selected heat sink;
 - (d) make sure that the transistor's metal mounting base cooled down enough;
 - (e) attach firmly the external heat sink to the transistor's mounting base using a screw with a spring washer [see Fig. 6(b); the transistor can be removed from the socket for this purpose provided attention is paid to mounting it back correctly];
 - (f) turn on the power supply.
 7. Check the possibilities to improve the operating conditions using the selected radiator:
 - (a) in the ScopeView program click *Record*, choose the location and name of the new target file, and accept;
 - (b) open the *Output* window by clicking *Scope*;
 - (c) make sure, that no cables are touching the transistor package not the load resistor;




Before performing the following sub-steps, read them entirely to the end.

- (d) touch the probe thermocouple to the transistor's metal mounting base [so not to the heat sink attached to it nor to the plastic element of the case; see Fig. 6(b)];
- (e) start the recording in the ScopeView program – button *Run*;
- (f) turn on the pulse generator;
- (g) observe the thermometer readout and when:
 - the critical package temperature is achieved (ca. 130 °C),
 - or the package temperature stabilizes (roughly),
 - or the waveform fills in (horizontally—with respect to the time axis) about 90% of the ScopeView window,

perform the following sub-steps in the given order;

- (h) stop the data recording in the ScopeView program – button *Stop*;
- (i) turn off the pulse generator.

Table 1. Heat sinks for the TO220 package available in the laboratory

Shape			
Designation	D03	D01A	HS-132-38
Surface	not blackened	blackened	blackened
$R_{th(s-a)}$	31 K/W	21 K/W	11 K/W

8. Turn off the power supply and wait until the LED signalling the supply of the power circuit turns off. Disconnect the supply from the circuit.
9. Finish your work with the multimeter:
 - (a) in ScopeView, close the *Output* window, then close the *Control Panel* window;
 - (b) close the multimeter connection by clicking *Power*, then close the application by clicking *Exit*;
 - (c) turn off the multimeter and disconnect the communication cable from it, while not removing the cable from the COM socket of the computer;
 - (d) detach the temperature probe from the multimeter.
10. Disconnect the circuit with the exception of components covered in step 11.
11. When the heat sink cools down, dismount the transistor from the screw terminal. Tighten back the screws in the screw terminal. Detach the heat sink from the transistor.

6. Result Elaboration and Analysis

6.1. Computer simulation

Numerical data

1. Collect in one single table the results read out from waveforms in Probe for 2 (* 3) switching frequencies:
 - (a) the energy dissipation in each of the four semiconductor switch operating states W_D ;
 - (b) the peak value of the instantaneous power loss $p_{D(pk)}$ in each of the 4 operating states.

To facilitate further actions, express values for all the four states in a same unit. Values of a same physical quantity for different switching frequencies should be located directly beside or below each other.

2. Complete the result table of step 1 by calculating (see Manual 3^A, Ref. D):
 - (a) total energy dissipation during one switching period $W_{D(tot)}$, according to Eq. (10.58) in the above reference, by summing the four components of the integral W_D read out in Probe and found in the result table;
 - (b) switching period T_s ;
 - (c) total average power loss P_D , according to Eqs. (10.59) and (10.60) combined to give:

$$P_D = f_p W_{D(tot)} = \frac{W_{D(tot)}}{T_p} \quad (6.1)$$

- (d) static average power loss $P_{D,stat}$, still based on (6.1) but with W_D restricted to the contributions of static states only;
- (e) dynamic average power loss $P_{D,dyn}$, still based on (6.1) but with W_D restricted to the contributions of dynamic states only.

Components of dissipated energy and power for medium switching frequency

3. Based on the results of steps 1–2 for the frequency $f_{s,ini}$, analyse the relation between the instantaneous power loss and the energy dissipated in the transistor:
 - (a) in which (one or more) of the 4 operating states does the instantaneous power loss attain its largest peak values $p_{D(pk)}$?
 - (b) in which (one or more) of the 4 operating states is the greatest amount of energy W_D dissipated?
 - (c) do the largest instantaneous power and the greatest amount of dissipated energy occur in the same or in different operating states of the transistor?
 - (d) explain the above observations based on relationship (4.1), optionally referring to the saved instantaneous power loss p_D waveform.
4. Based on the results of steps 1–2 for the frequency $f_{s,ini}$, analyse the relation between the instantaneous power loss and the average power loss:
 - (a) compare the instantaneous power loss in the static and in the dynamic states with the static average power loss $P_{D,stat}$ and the dynamic average power loss $P_{D,dyn}$;
 - (b) based on the definition of the average power (see Manual 0, Ref. C) and the equations derived from it (see Manual 3^A, Ref. D, or Manual 0, Ref. G) explain, why the average power is so low compared to the instantaneous power losses;
 - (c) do the results obtained justify the assumption (see Manual 3^A, Ref. D) that the contribution of the power losses in the blocking (off) state to the static average power loss is negligible?
 - (d) does the expected, specific relationship between the average power loss and the on-state instantaneous power loss (see Manual 3^A, Ref. D) hold?

Effect of switching frequency

5. Analyse the values of energy dissipated at different switching frequencies:
 - (a) which of the 4 components of the energy dissipated in the transistor remain constant, and which ones change with the switching frequency and in what way?
 - (b) based on the waveforms saved in steps 4.3/8–10, specify operating states whose duration depends on the driving waveform frequency, and those whose duration depends on the transistor's properties?
 - (c) explain your observations of sub-step (a) based on the relationship (4.1) and your statements of sub-step (b), also referring to the saved waveform of the instantaneous power loss p_D (does this waveform change and in what way?)
6. Analyse the changes in contributions of the particular components to the total energy dissipation in the transistor as a function of the switching frequency:
 - (a) based on the results of steps 1–2, plot a graph of energy dissipation in the transistor in its 4 operating states as a function of the switching frequency, in the form of a percent cumulative bar graph (one single including all the frequencies for which results are available);

A **cumulative bar graph** (in office packages this name usually refers only to horizontally oriented graphs, while the traditional graph with vertical orientation we are interested in may be named a 'column graph') is intended for visual presentation of quantities composed of several components. In such a graph, bars corresponding to the particular components are not placed side by side but stacked on each other. Thanks to this presentation form, it is easier to determine how important the contribution of each component is. At the same time, the total height of the bar corresponds to the total value (sum of the components) of the given physical quantity.

A variant of the cumulative bar graph is the **percent cumulative graph** (called '100% stacked column' in Microsoft Office and 'column percent stack' in OpenOffice.org). Such a graph does not present values directly (absolute values). Every bar has the same height described as 100% which corresponds to 100% of the total value. Particular component bars have heights corresponding to their relative contribution (relative values) to the total value.

In accordance with reality, the Y-axis should be labelled as energy ratio $W_D/W_{D(\text{tot})}$.

- (b) how does the contribution of the particular components change along with the switching frequency?
 - (c) explain your observations based on results from step 5.
7. Analyse the evolution of the total average power loss and its components:
- (a) based on the results of steps 1–2, plot a graph of the average power loss as a function of the switching frequency, showing the contributions of the static and the dynamic components, in the form of a cumulative bar graph (but not a percent one now), where the lower bar should correspond to the static states and the upper one, to the dynamic states;
 - (b) how do the particular components and the total average power loss change along with the switching frequency?
 - (c) explain the observations—relate them to the results of steps 5–6 while referring to the appropriate equations (see Manual 3^A, Ref. D, and Manual 0, Ref. G); in particular, answer the questions:
 - why does the static average power loss remain constant despite energy dissipation in static operating states changing?
 - why does the dynamic average power loss change despite energy dissipation in dynamic operating states remaining constant?
 - (d) * plot the dynamic average power loss $P_{D,\text{dyn}}$ as a function of the switching frequency f_s ;
 - (e) * determine the character of the plotted relationship; state whether it agrees with theoretical predictions (see Manual 3^A, Ref. D, or Manual 0, Ref. G)?
8. Taking into account the facts and relationships visible in the graphs of steps 6 and 7, when we want to minimise power loss, will we apply the criterion of small conduction (static) losses or of small switching (dynamic) losses in transistor selection? Analyse the problem and give answers for two different cases separately: one of low and one of high switching frequency. Provide justifications based on the results mentioned above.

6.2. Elaboration of measurement results

Starting the Scilab program

1. Run the numerical analysis package Scilab.
2. Read in the script containing functions necessary for heating curve processing by typing the command

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

where *script_path* is the path for the script file *temperatura.sce*.

3. To simplify access to measurement data files (ScopeView files), change the working directory to the directory containing these files by typing the command

```
cd('measurement_result_path');
```

Determining the heating process parameters

4. Load the results of heating curve measurements from the two saved TXT files (for the case without and with a heat sink) to two separate matrices by typing the command (twice, using different matrix names):

```
matrix_name=wczytaj_m3660('file_name.txt');
```

5. In Scilab, plot in a single graph waveforms of case temperature as a function of time, for both recorded cases:

- (a) type the command

```
wykresl(matrix_name);
```

If the above command is preceded by an assignment of the result to an arbitrarily named curve object (e.g., *curve1=*), then this object can later be used to change the colour of the curve with the command *zmien_kolor(object_name, colour_number)*. The curve can be removed by running the command *usun_krzywa(object_name)*. If necessary, all the graph can be cleared with the command *clf()*.

- (b) save the graph by choosing *File ▶ Export* from the menu and selecting the *Enhanced Meta File* format.

6. For both cases, determine heating curve parameters using an exponential approximation:

- (a) calculate the approximation parameters and display the approximating curve by typing:

```
[TA, TCst, tau, TC_apr]=aproxymacja(matrix_name);
```

The function *aproxymacja* calculates the following: the ambient temperature T_a [assuming that it is equal to the initial case temperature $T_c(0)$], the real or hypothetical (in the case without a heat sink) steady-state case temperature under $T_{c(st)}$, the effective thermal time constant τ_{th} and a matrix $T_{c,apr}$ containing the coordinates of the consecutive points along the approximating curve.

In rare cases the approximation may fail. Usually this is caused by a long initial section in the input data where the temperature remains constant. It happens when the turn-on of the circuit has been delayed during measurements. In such a case, make a backup copy of your TXT file and try to cut the lines covering this section from the original file. Next, load the file once again in Scilab and call the function *aproxymacja* again. If this does not help, make a similar cut at the final part of the data.

- (b) save the graph;

- (c) display and write down the steady-state case temperature $T_{c(st)}$ as determined by the algorithm through curve extrapolation, by typing:
- TCst
- (d) * display and write down the effective thermal time constant τ_{th} , by entering the variable name tau;
- (e) * for the case without a heat sink, display and write down the ambient temperature T_a , by entering the variable name TA;
- (f) gather the numerical results in one single table (all the values, as read out for both cases).
7. For both cases, based on the steady-state case temperatures $T_{c(st)}$ determined in step 6, from the Fourier's law of heat conduction in the form of Eq. (29-2) in Ref. A, applied to an appropriate fragment of the transistor's thermal circuit (Ref. A, Fig. 29-2), calculate the estimated steady-state junction temperature $T_{j(st)}$. Assume that the average power loss for the investigated case was properly predicted by means of simulation (the value read out in step 4.4/3). The required thermal resistance was read out from the transistor's data sheet in step 4.4/5. Add the results to the result table of step 6.

6.3. Analysis of measurement results

Thermal safety

1. Compare the voltage waveforms obtained through simulation and saved in step 4.4/4 to those measured in the real circuit and saved in step 5.1/21. Determine if transistor's operating conditions during simulations and measurements were the same with respect to switching frequency and supply voltages of control and power circuits (the amplitude of u_{GS} voltage, and u_{DS} voltage in the transistor's blocking state, respectively).
2. Based on the graphs and numerical results obtained in step 6.2/7, state:
 - (a) how the steady-state junction temperature $T_{j(st)}$ changed as a result of attaching the heat sink;
 - (b) whether the calculations of the transistor's thermal circuit gave a correct answer on:
 - safe operation of the device without a heat sink, i.e. if, based on calculations of steps 4.4/5–6, it was properly predicted that the transistor would or would not operate safely (give the basis for your statement of safe or unsafe operation);
 - the required countermeasures, or the required heat sink thermal resistance, i.e. if applying a heat sink conforming to the requirement calculated in step 4.4/7 indeed asserted the transistor's safe operation.
3. * Carry out a quantitative analysis of the heat sink's effect on the parameters of the cooling system:
 - (a) for both cases (with and without a heat sink), using the Fourier's law of heat conduction, Eq. (29-2) in Ref. A, estimate the effective case-to-ambient thermal resistance $R_{th(c-a)}$, while:
 - using the relevant results of step 6.2/6,
 - assuming that the average power loss in the investigated operating conditions was properly predicted by means of simulation in step 4.4/3;
 - (b) based on results of sub-step (a) and the thermal time constant τ_{th} values determined in step 6.2/6, using the traditional thermal time constant definition [Ref. A above Eq. (29-13); Eq. (29-9) should not be used as it does not concern a thermal time constant for an exponential temperature rise], calculate the effective thermal capacitance $C_{th,eff}$:
 - of the metal mounting base of the case (the case without a heat sink),
 - of the case with the heat sink attached;
 - (c) add the results to the result table of step 6.2/6;
 - (d) do the estimated $R_{th(s-a)}$ values agree with the known parameters of the transistor (as given in its data sheet) and of the heat sink used (Table 1) considering the thermal circuit model applied (Ref. A, Fig. 29-2)?
 - (e) does the change in the estimated $C_{th,eff}$ value due to attaching the heat sink agree with the physical interpretation of this parameter (see Ref. A, Section 29-2-2)?

On-state resistance

4. * Using the graticule in the oscilloscope images of u_{DS} waveform recorded in step 5.3/5, read out the values of the drain-source on-state voltage $U_{DS(on)}$ at $T_j \approx T_a$ (start of heating process) and at $T_j \approx T_{j(max)}$ (end of heating process).
5. * Based on the values of $U_{DS(on)}$ obtained in the previous step:
 - (a) compare the values for the two temperatures of the semiconductor structure;
 - (b) explain the results taking into account that the drain-source circuit of the MOSFET transistor can be represented as the on-state resistance $R_{DS(on)}$ (see Ref. C [14], Section 1.2.9, Static Characteristics, Manual 3^A, Ref. A, Section 10.2.1);

- (c) relate the results to the characteristics of the on-state resistance vs. temperature given in the transistor's datasheet (see Ref. C [14], Section 1.2.9, Static Characteristics);
- (d) based on the analysis above, state whether the temperature effect on device operation should be taken into account during design of the transistor's heat flow system or it can be disregarded (see the formula for the static on-state power loss, Manual 3^A, Ref. A, Section 10.2.1)?

Voltage safety

6. * Based on u_{DS} waveforms recorded in step 5.2/1–2:
 - (a) using the graticule in the saved oscilloscope images, read out the peak values $u_{DS(pk)}$ in the case without and with the clamping diode;
 - (b) state whether the rule-of-thumb for voltage-based transistor selection given in step 4.1/7(b) allows avoiding transistor breakdown in a real circuit unconditionally or some designer action is assumed by default? what would have happen had we selected a transistor with a rated voltage exactly equal to the value calculated initially in step 4.1/7(b) and had not used the clamping diode?
7. * Analyse the operation of the diode (see Ref. E):
 - (a) based on the oscilloscope images above, describe the changes that happened in the circuit after the diode had been connected;
 - (b) try to explain the operation of the clamping diode.

Hint: The voltage across the diode is equal to the voltage potential difference between the transistor's drain and the positive terminal of the supply voltage U_{DD} . How will the diode be biased (forward or reverse) at the instant of overvoltage occurrence (u_{DS} increasing above U_{DD})? Will the voltage across the diode in this operating state be significant as compared to U_{DD} ? Will the diode resistance be significant as compared to R_L ? What will be the resulting approximate value of u_{DS} ?

6.4. Transistor rated parameters

1. * Check whether the datasheet rated parameters $P_{D(\text{rat})}$ and $I_{D(\text{rat})}$ of the selected transistor were calculated in the way described in Ref. C [14], Section 1.2.9.
2. Assess the utility of the ratings provided in the datasheet: the maximum continuous drain current $I_{D(\text{rat})}$ (consider the value shown on the transistor list, i.e. the one for $T_c = 25\text{ }^\circ\text{C}$) and the maximum power $P_{D(\text{rat})}$:
 - (a) were the abovementioned values exceeded in the investigated circuit?
 - (b) comment on your conclusion from step 4.4/6 (regarding maintaining safe operating conditions) in relation to this fact (see Ref. C [14], Section 1.2.9, and [16]).
3. Considering the conclusions from step 6.3/2, assess the utility of the maximum continuous drain current at the case temperature T_c of $100\text{ }^\circ\text{C}$ (see Ref. C [14], Section 1.2.9, and [16]):
 - (a) is it a good indicator of the transistor's capabilities in terms of (safely) conducting current?
 - (b) can this current be safely conducted by the transistor unconditionally or some additional measures are needed from the circuit designer?

7. Expected Report Contents

Circuit components

1. Parameter values of the u_g source, determined according to steps 4.2/5–6
2. Required transistor parameters determined in step 4.2/7 with performed calculations (i.e. minimum values of rated current and rated voltage)
3. Designation of the transistor selected in step 4.2/8 and its data from data sheet demonstrating that requirements have been met (i.e. rated current for 100 °C case temperature and rated voltage)

Energy dissipation and power loss

4. Voltage, current, power and energy waveforms obtained for different switching frequencies, recorded in step 4.3/8–10 (i.e. for each of the 2 [* 3] frequencies, a plot showing at least one full switching period and two plots showing turn-on and turn-off separately, unless they are clearly visible in the full period plot)
5. Simulation result table, according to step 6.1/1–2 (i.e. numerical values read out of plots obtained from simulations in steps 4.3/6, 9, 10 and calculation results from step 6.1/2, for 2 [* 3] frequencies)
6. Result analysis and conclusions, according to step 6.1/3–8

Cooling system

7. Plots of voltage, current, instantaneous power and average of instantaneous power obtained for the junction temperature of 150 °C, recorded in step 4.4/4 as well as the value of average power loss read out in step 4.4/3 (i.e. the average power value that has been used in transistor cooling system design and the waveform from which it has been read out)
8. Oscilloscope image proving proper operation of the real low-side switch circuit, recorded in step 4.1/21, and its comparison to the plot obtained through simulation,

- saved in step 4.3/8, according to step 6.3/1
(i.e. u_{GS} and u_{DS} waveforms with at least one full switching period visible)
9. Maximum allowed power loss without a heat sink calculated in step 4.4/5, conclusion regarding safe operation conditions formulated in step 4.4/6, heat sink thermal resistance calculated in step 4.4/7 (if it proved necessary) and used thermal resistance values read out of transistor's data sheet; all formulae used and calculations made
 10. Thermal resistance of the heat sink finally chosen written down in step 4.3/6c (i.e. thermal resistance of the real heat sink actually used)
 11. Heating curves without and with a heat sink recorded from the multimeter in Section 4.3 and plotted in Scilab, according to step 6.2/5 (i.e. temperature vs. time plots)
 12. Table containing numerical values of heating curve (* and cooling system) parameters without and with a heat sink, as well as approximating curve plots for both cases, according to steps 6.2/6–7 [* and 6.2/3(a)–(b)] (i.e. case and junction temperatures [* as well as ambient temperature, thermal time constant, effective thermal resistance and capacitance])
 13. Qualitative analysis of heat sink's effect on the circuit, according to step 6.3/2(a)
 14. Comparison of calculations (Section 4.4) and measurement results (Sections 5.3 and 6.2) with respect to the correctness of the former, according to step 6.3/2(b)
 15. * Quantitative analysis of the heat sink's effect on cooling system parameters, according to step 6.3/3(d)–(e)

Effect of temperature on the on-state resistance

16. * Waveforms of u_{DS} voltage at a junction temperature close to T_a and at one close to $T_{j(max)}$ recorded in step 4.3/5 (i.e., waveforms recorded at the beginning and at the end of heating process without a heat sink)
17. * Values of on-state drain-source voltage $U_{DS(on)}$ read out of waveforms for the two temperatures, according to step 6.3/4
18. * Analysis of temperature's effect on voltage drop and static power loss, according to step 6.3/5

Voltage safety

19. * Oscilloscope image (repeated) recorded in step 4.1/22 with indication of the operating state where u_{DS} voltage exhibits highest values, according to step 4.2/1(a) (i.e., u_{GS} and u_{DS} waveforms with at least one full switching period visible)
20. * Waveforms of u_{DS} voltage in the appropriate operating state, in the circuit without a clamping diode and in the one containing the clamping diode, recorded in steps 4.2/1(d) and 4.2/2(d), clearly labelled
21. * Peak voltage values $u_{DS(pk)}$ read out of the above waveforms and voltage safety analysis in the context of rated voltage and the rule-of-thumb, according to step 6.3/6
22. * Operation description of the clamping diode, according to step 6.3/7

Transistor parameters

23. * Comparison of rated parameter values given in the data sheet to values calculated using appropriate formulae, according to step 6.4/1; used parameter values read out of transistor's data sheet; all formulae used
24. Utility analysis of the transistor ratings provided in the datasheet, with their values quoted, according to steps 6.4/2–3

8. Required Knowledge

8.1. Prerequisites

- Power MOSFET control (drive) and main (power) terminals (see Manual 0, Ref. H, or Manual 3^A, Ref. A)
- Voltage and current waveforms during VDMOS switching with resistive load (see Manual 3^A, Fig. 6 and Ref. C considering the purely resistive load case, and Manual 0, Ref. G)
- Power loss in the MOSFET transistor (drain circuit): instantaneous power formula and waveform during switching, on-state power loss, energy relationship to instantaneous power (see Manual 3^A, Ref. D, and Ref. A, Section 10.2.1; Manual 0, Ref. G)
- Switched-mode control waveform parameters: duty cycle, switching period and frequency (see Manual 3^B, Section 2.2)
- DC voltage chopper circuit topology and operation (see Section 4.1)

8.2. Test scope

1. Average power definition. Power loss and energy dissipated in the MOSFET transistor (drain circuit): instantaneous power (formula), average power (formula), energy (formula), static (formula) and dynamic (without formulae) components of the average power. (see Manual 0, Refs. C and G; Manual 3^A, Ref. D; report)
2. Dependence of energy dissipation and average power loss on switching frequency: total values and contributions of the different operating states of the transistor as a switch, with explanation of observations. Parameters important for transistor selection with the aim of minimising power loss depending on switching frequency. (see report)
3. Thermal resistance: definition, unit [Moh]. Heat flow path for a semiconductor device cooling system [Moh]. Fourier's law of heat conduction in its form applied in electronic circuit design (i.e., the relationship between temperature, power loss and thermal resistance—equation) [Moh, 14]. Equivalent electrical circuit: characteristic resistances and temperatures; voltage and current equivalents [14]. Thermal resistances for a cooling system with and without a heat sink [14]. (see Ref. A)
4. Application of the Fourier's law of heat conduction and the electrical equivalent circuit of a thermal system in calculations of temperatures, maximum power, maximum current and heat sink thermal resistance: continuous power dissipation, pulse power dissipation for higher frequencies (average temperature) (formulae). Thermal safe operation conditions. (see Ref. A [14, 16], report)
5. Device case heating curve and the effect of the heat sink on it. (see report)

6. Avalanche breakdown: physical mechanism (in brief, without formulae), practical consequences for device safety.
(see Ref. C [14], Section 1.2.7; Manual 0, Ref. L, Section 2.1.3)
7. Thermal breakdown: physical mechanism of thermal instability in a reverse-biased PN junction (in brief, without formulae), practical consequences for device safety; risk level and hazard causes for unipolar (MOSFET) and bipolar (BJT) devices (in brief, without details of physical phenomena).
(see Refs. B, C and D)
8. Transistor selection for the low-side switch circuit: operating current and voltage estimation based on the ideal switch assumption, rule-of-thumb for voltage-related selection, rated current and its practical application.
(see Ref. C [14], [16]; report)

When results included in your report are concerned, restrict to the qualitative aspect (mutual relationships and character of changes) disregarding the quantitative one (specific numerical values).

9. References

- [1] Benda V., Gowar J., Grant D. A.: *Power Semiconductor Devices: Theory and Applications*. Wiley, 1999. ISBN 0-471-97644-X.
- [2] Mohan N., Undeland T. M., Robbins W. P.: *Power Electronics: Converters, Applications, and Design*. 3rd Ed. Wiley, 2003. ISBN 0-471-22693-9.
- [14] *Power Semiconductor Applications*. Philips Semiconductors, 1994.
- [15] *Power dissipation and its linear derating factor, silicon limited drain current and pulsed drain current in MOSFETs*. Rev. 1. STMicroelectronics, June 2006. Application Note AN2385.
- [16] *Current Ratings of Power Semiconductors*. International Rectifier. Application Note AN-949.
- [17] *The Do's and Don'ts of Using MOS-Gated Transistors*. International Rectifier. Application Note AN-936.