



POWER DEVICES AND SYSTEMS LABORATORY

Exercise 3P

Switched-mode operation of power transistors

Power MOSFET

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Exercise Introduction

1. Exercise Aim and Plan

The aim of This exercise is to analyse the operation of a power transistor used as a semiconductor switch. A MOSFET will be investigated as an example representative of this group of devices. This, in addition, will make it possible to get acquainted with the field-effect control mechanism through an insulated gate.

2. VDMOS Switching

2.1. Recommended reading

Ref.	Textbook	Excerpt	Equivalent in the Polish Manual	Complementary Reading	Complements in this Manual
A	Ben	10, 10.1, 10.1.1, 10.1.2, 10.2, 10.2.1	2.1, 2.2, 3.2; Ref. [1]	[13] 4, 6.3	
B	Ben	10.2.2 incl. Fig. 10.6	2.3, 2.4.e	[13] 6.1	
C	Ben	10.3, 10.3.1, 10.3.2	2.4, 2.5.a–d, 2.6.a		
D	Wil	6, 6.1, 6.1.1, 6.1.2	2.4a–g, 2.5.a–d		
			2.6.b		2.2

Note: Ref. D is based on the example of a BJT where terminal names and the control mechanism are different from a MOSFET. Other than that, results and conclusions stay valid for any power transistor.

Additionally, from Manual 0 references:

Ref.	Textbook	Excerpt	Equivalent in the Polish Manual	Complementary Reading	Complements in this Manual
0 G	Ras	6.3.2	2.5.e		
0 H	Ben	3.1.5	2.1.a		

2.2. Practical measurements of temporal parameters

The definitions of MOSFET temporal parameters used in the dynamic state analysis in Ref. C can be called “physical” since they represent the actual duration of physical processes occurring inside the device. Unfortunately, it is impossible to use them in practice. Due to the fact that all transients theoretically end only in infinity, it is impossible to determine exactly when, for example, the u_{DS} voltage reaches its steady-state value of $U_{DS(off)}$.

Therefore, in measurement and design practice, technical definitions of temporal parameters according to international standard IEC 60747-8-4 are applied. It is based on them that the parameters given in transistor data sheets are measured. In the technical definitions, instead of ideal steady states, the moments when waveforms attain the characteristic relative values of 10% and 90% are considered. Relative value here means a value related to the steady-state high level.

In the case of the MOSFET, the u_{GS} and the u_{DS} voltages are reference waveforms wherein the initial value of u_{GS} should be 0 V, as shown in Fig. 1. Thus, the considered relative values can be formally described with the formulae:

$$u_{GS(r)} = \frac{u_{GS}}{U_{GS(on)}} \quad (2.1)$$

$$u_{DS(r)} = \frac{u_{DS} - U_{DS(on)}}{U_{DS(off)} - U_{DS(on)}} \quad (2.2)$$

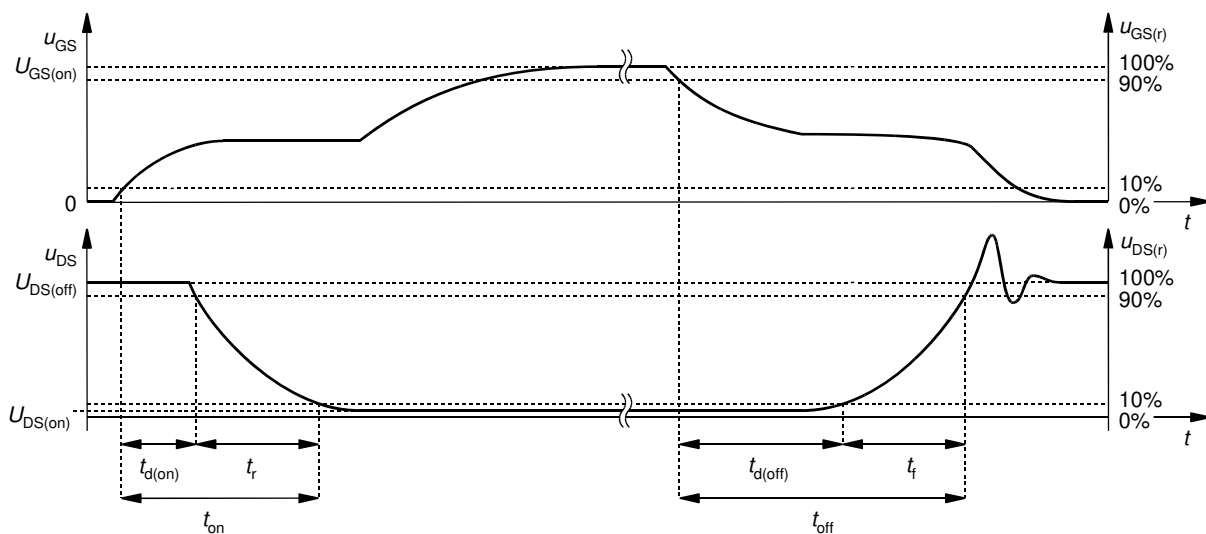


Fig. 1. Technical definitions of power MOSFET temporal parameters according to IEC 60747-8-4

The technical definitions of MOSFET temporal parameters can be expressed in words as follows:

- the turn-on delay time $t_{d(on)}$ is the time interval from the moment in which the relative value $u_{GS(r)}$ of the rising u_{GS} voltage reaches 10% to the moment in which the relative value $u_{DS(r)}$ of the falling u_{DS} voltage attains 90%;
- the rise time t_r is the time interval during which the relative value of the u_{DS} voltage drops from 90% to 10%;
- the turn-off delay time $t_{d(off)}$ is the time interval from the moment in which the relative value of the falling u_{GS} voltage attains 90% to the moment in which the relative value of the rising u_{DS} voltage reaches 10%;

- the fall time t_f is the time interval during which the relative value of the u_{DS} voltage rises from 10% to 90%.

The total turn-on and turn-off times are defined as sums of the relevant component time intervals, so their technical definitions are identical to the physical ones.

Special measurement systems are designed so as to obtain waveforms maximally resembling ideal ones. However, effects of parasitic components may be observed in the form of overcurrents, overvoltages and oscillations, as illustrated in Fig. 1 for the u_{DS} voltage during turn-off. If, as a result of such distortions, the voltage level referred to in a definition is crossed several times, it is always the first crossing of this level by the relevant that should be considered. This is due to the fact that even distorted voltages cannot change more rapidly than allowed by the physical mechanisms acting in the semiconductor structure. Thus, the reference level is always reached within a time resulting from the device properties, which are what we want to investigate. On the other hand, the fact of crossing the reference level (overvoltage) and the following tendency toward the steady state (further oscillations) results from the parameters of the operating circuit and should therefore not be taken into account.

Analysing the data sheet of the transistor under investigation, it can be seen that its manufacturer gives the temporal parameter values for strictly defined supply and drive conditions. These are therefore sample values, enabling an indicative comparison of different devices one with another. In a real circuit, these parameters may be significantly different, since the effect of the transistor's operating circuit and conditions is significant.

3. Measurements

3.1. Experimental circuit

The schematic of the experimental circuit, which is a chopper using the low-side switch topology, is presented in Fig. 2. The points marked in the schematic are wired to sockets on the front panel. Moreover, points G, D and S are wired to the blue screw terminal, allowing a transistor T to be inserted in the circuit. The IRF540N MOSFET will be investigated in this exercise. A resistive (R_L) or an inductive (Z_L) load will be connected through front panel sockets specified further in this manual.

The transistor is driven from a built-in generator of a pulse wave whose frequency $f_p = 10$ kHz and duty cycle $D = 0.5$. Between the generator and the transistor's gate are found a IR2117 gate driver and a gate resistor whose resistance $R_G \sim 100 \Omega$. The amplitude of the pulsed gate control voltage is approximately equal to the supply voltage of the control circuit, $U_{GG} = 10$ V. The generator is started by pressing one of the two buttons on the front panel (switch K in Fig. 2): the red one, to switch it on continuously, or the green one, to switch it on just for the time the button is depressed. The generator's operation is indicated by a yellow LED.

The oscilloscope will only refresh data in its memory while the generator is operating. Thus, it is necessary to activate the generator after each change of settings. This is also valid when changes are only made on a measurement device (oscilloscope or current probe). Only after new pulses are 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.

In this exercise, due to the risk of transistor or load overheating, the generator should be switched off for most of the time and only turned on for short time intervals to refresh waveforms on the oscilloscope. Therefore, only the green button should be used to activate the generator, being depressed for no longer than one second.

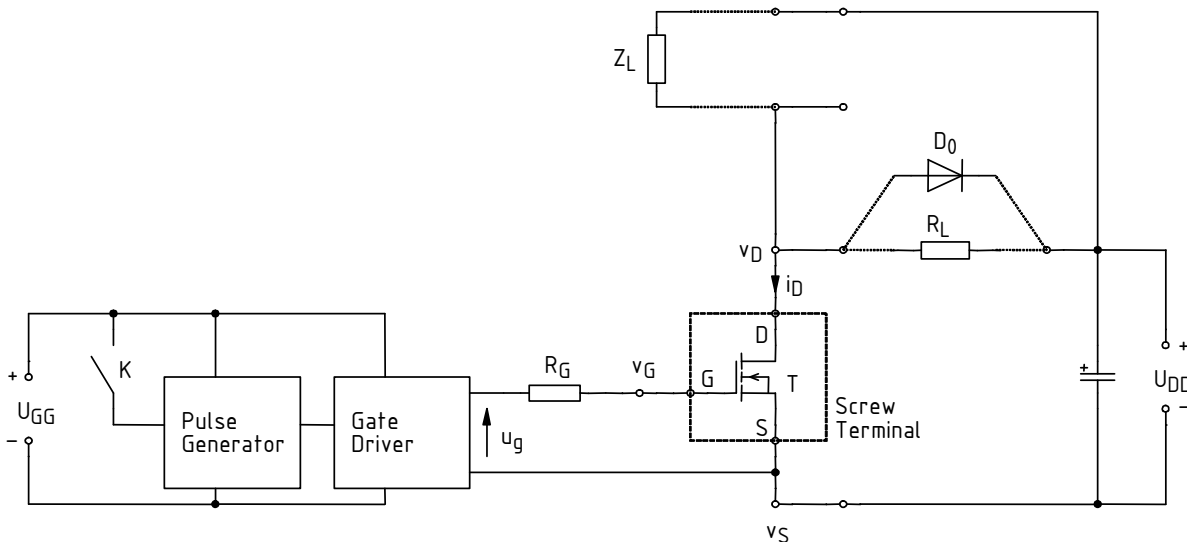


Fig. 2. Low-side switch experimental circuit schematic

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} and gate supply in Section 3.2);
- one with sections connected in series, which will enable a higher voltage to be obtained, for the power loop (U_{DD}).

The circuit enables measurements of inter-terminal voltages and drain current of the device under investigation. Voltage measurements are performed using voltage probes appropriately connected to banana sockets labelled as v_S , v_G and v_D in Fig. 2. 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 needs.

Current measurements are performed by clamping a current probe around the wire fragment led above the front panel and marked as i_D in Fig. 2. 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. Principal circuit resistance

The block diagram of the measurement set-up is presented in Fig. 3. It should be assembled in the way described below and following the order of actions specified.

1. Make sure that the power supply is switched off. Set it to the independent section operating mode (two buttons in the middle of the front panel, whose functions are explained above them on the panel). Turn all the knobs of the power supply down to zero (extreme anticlockwise position).
2. Switch the power supply on.

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

3. Mount the transistor under investigation in the three-pin terminal block on the circuit's panel, according to the circuit schematic (compare Fig. 2 to the drawing on the panel) and to this transistor's terminal arrangement shown in the TO-220 package data sheet which is attached to this manual. Tighten all the three mounting screws.
4. Make sure that the power circuit loop remains open, i.e. that no component is connected to any front panel socket located right of and above the transistor.
5. Using banana-terminated wires, bring voltage from one of the adjustable sections of the power supply between the gate and the source of the transistor so that the u_{GS} voltage is positive, i.e. connect:
 - the "+" socket of the power supply to the transistor's gate (v_G socket),
 - the "-" socket of the power supply to the transistor's source (v_S socket),
 - additionally grounding the negative terminal by connecting the "-" socket to the GND socket.

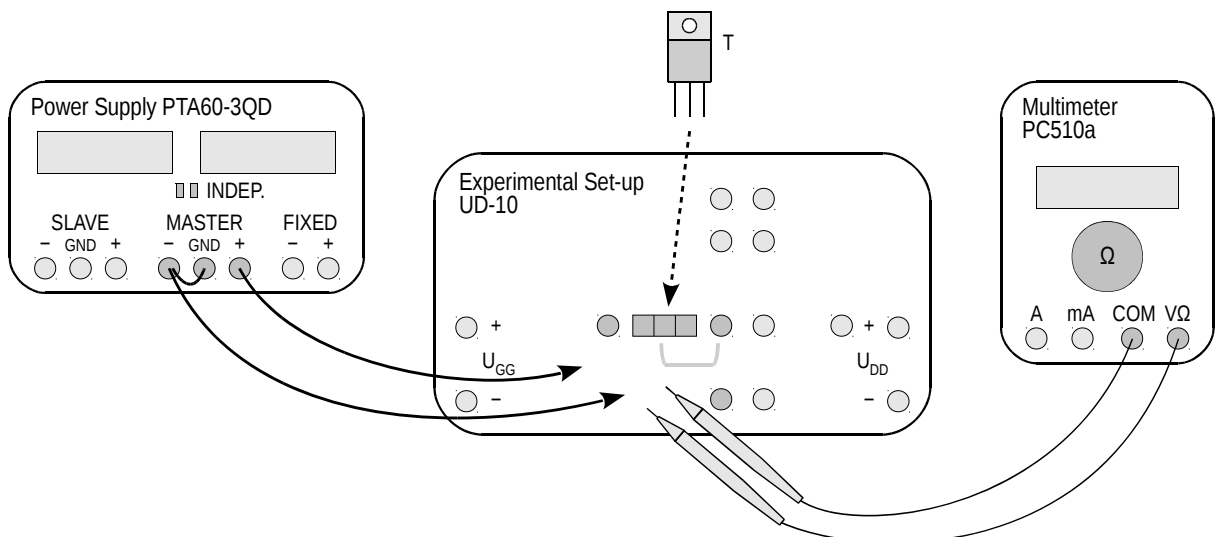


Fig. 3. Block diagram of the measurement set-up for drain-source resistance measurement

6. Slightly increase the limiting current (*Current* knob) of the power supply until the red current limiting indicator goes out.
7. Switch the multimeter on and set it to the resistance measurement mode. Connect original test probes to the appropriate (for resistance measurements) terminals of the meter.

If a 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 might become erroneous.

8. Using the multimeter, measure the drain-source resistance R_{DS} of the transistor, by touching its appropriate leads mounted in the terminal block (not to any other points in the measurement set-up located anywhere else) with the test probes:
- the drain lead, with the probe connected to the meter's common socket (COM),
 - the source lead, with the probe connected to the meter's resistance measurement socket (Ω).

Write down the indication of the meter R_{DS} with an accuracy of two significant digits.

Before proceeding with the following step, connections and settings must be checked by the teacher. To avoid losing time, execute step 3.3/1 while waiting for the check.

While carrying out the following step, the voltage set cannot exceed 15 V at any single moment as this might cause the transistor to break down.

9. Gradually increase the power supply voltage (not exceeding 10 V, however). Write down the U_{GS} voltage at which the R_{DS} resistance drops drastically, i.e. by at least three orders of magnitude. Write down this resistance itself as well.

The expression "at least" means that the magnitude of the drop cannot be lower than the one given, whereas it can be larger. It does not mean that the magnitude of this drop must be exactly the one given, so you should not waste time for accurately setting the voltage to obtain any specific resistance value.

10. Measure the drain-source resistance when the transistor is fully on:
- (a) calibrate the meter for small resistance measurement:
 - short the tips of the test probes together,
 - wait for the meter's indication to settle,
 - with the probe tips still shorted together, push the *Range* button to start wire resistance compensation procedure,
 - the message "Shrt" (short) should show up on the display for 3 sec., after which a reading of 0 should be displayed,
 - open the test probe tips;
 - (b) set the voltage of 10 V on the power supply;
 - (c) touch the appropriate leads of the transistor mounted in the terminal block with the test probes:
 - the drain lead, with the probe connected to the meter's resistance measurement socket (Ω);
 - the source lead, with the probe connected to the meter's common socket (COM);write down the meter's indication R_{DS} .

11. Bring the supply voltage back to zero and switch the power supply off.

12. Switch the meter off.

3.3. Preparing for time waveform recording

Measurement circuit set-up

The block diagram of the measurement set-up is presented in Fig. 4. It should be assembled and configured in the way described below and following the order of actions specified. Connections existing at this moment and resulting from the previous section should not be removed; a procedure for their appropriate modification will be given further in this manual.

To avoid losing time, proceed with 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: independent (this should already be done within Section 3.2),
 - on the other power supply, which will be used for the power loop: parallel;
 - (c) turn all the knobs of both power supplies down to zero (extreme anticlockwise position);
 - (d) remove the short between the “-” terminal and the ground (GND terminal);

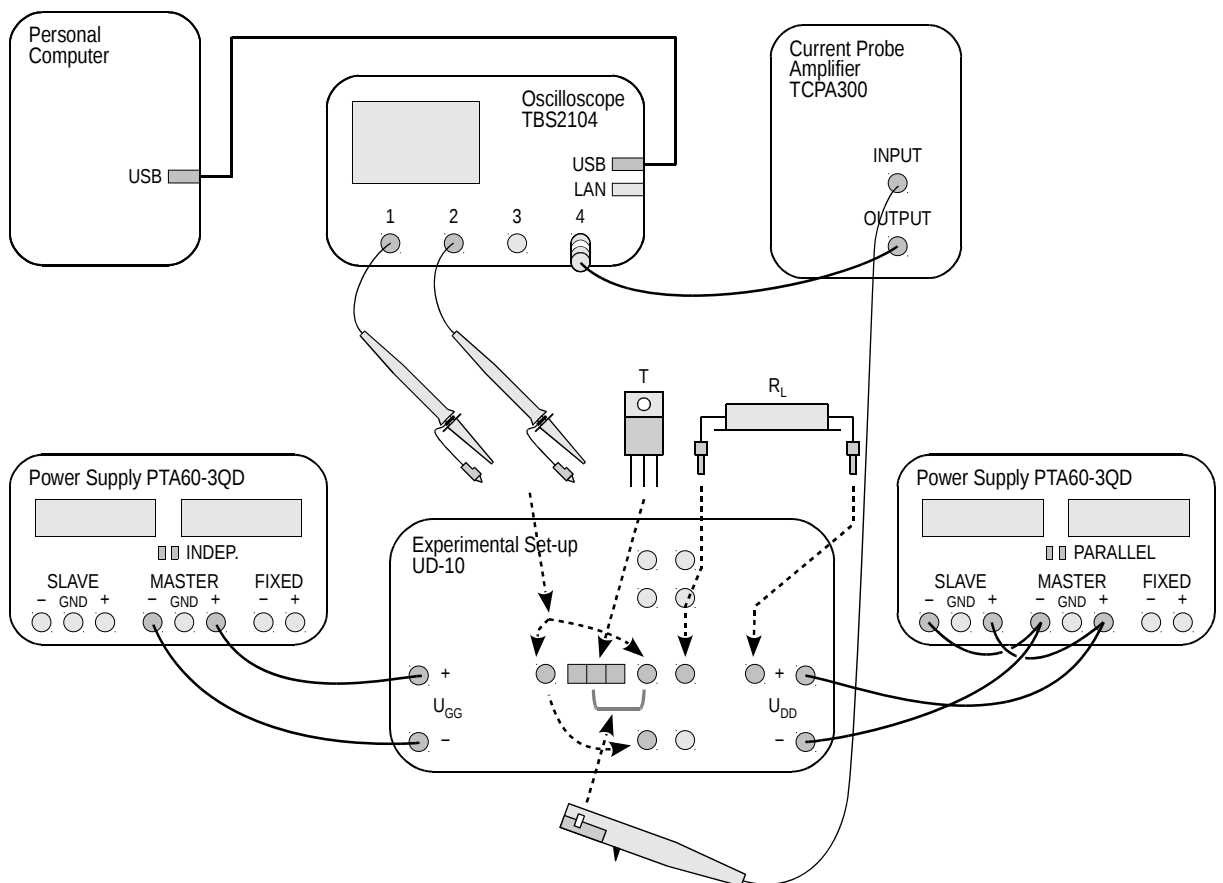


Fig. 4. Block diagram of the measurement set-up for recording time waveforms

- (e) 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 by switching over the wires now connected to v_S and v_G sockets, keeping the polarity as indicated on the power supply;
 - (f) with short wires, connect the “–” socket of the *Master* section of the other (power loop) supply to the “–” socket of the *Slave* section of the same supply; by analogy, connect the “+” sockets;
 - (g) connect the “–” and “+” sockets of the *Master* section of the power loop supply to the corresponding U_{DD} sockets on the circuit’s panel, keeping the polarity as indicated on the power supply.
3. From the web page, obtain and write down the power loop supply voltage U_{DD} and the desired load current I_o .
 4. Mount necessary components:
 - (a) applying Ohm’s law, calculate such a load resistor resistance R_L that with the power loop supply voltage U_{DD} obtained in step 3, after transistor is turned on, the current I_o determined in step 3 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);
 - (b) between the sockets marked in Fig. 4, connect a power resistor (50-watt, in a metal casing, with short lead wires and banana connectors) 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!

5. Connect two 10:1 attenuation voltage probes so that the gate-source voltage u_{GS} is measured in the oscilloscope’s channel 1 and the drain-source voltage u_{DS} is measured in channel 2. If just one of the probes has a ground connector available, it should be used to measure the u_{DS} 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 drain potential connector v_D , the transistor’s metal base, the load resistor’s leads as well as coil and clamping diode leads in the future).
 3. Before proceeding with the following step, connections must be checked by the teacher!
 4. Before executing each of the steps 6 and 8, read them first in their entirety, including any comments below!
6. Switch the control circuit power supply on. Set the control circuit supply voltage (*Voltage* knob) to 10 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.

7. Make sure that the pulse wave generator is inactive, which is indicated by the yellow LED extinguished under the K buttons. If not, turn off the generator by pushing the red button.
8. Energise the power loop:
 - (a) switch the power loop supply on;
 - (b) slightly increase the current limiting thresholds in both sections of the power loop supply (*Current* knobs) until the red current limiting indicator (*C.C.*) of the *Master* section goes out (the respective indicator in the *Slave* section will still be on);
 - (c) using the Master section Voltage knob (which simultaneously adjusts both sections in the parallel mode), set the power loop supply voltage to the value determined in step 3; in case current limiting activates, act as in step 6;

a red LED indicator should light up on the circuit's panel;

Under correct circuit operation in its idle state (the generator turned off), 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.

- (d) if no signs of incorrect circuit operation are observed, increase the current limits in both sections of the power loop supply to their maxima.
9. 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_3p_tbs2014.set*;
 - click *Send Settings* (not *Send to multiple*);
 - return to the *Screen Capture* tab.

Trial measurement

Turning the transistor on for longer than one second, including permanently (using the red button), either during trial measurements or investigations proper, may cause the device to become damaged due to overheating!

10. Generate a train of switching pulses for the transistor by pushing (for not more than one second) the green button on the circuit's panel. On the oscilloscope, the message "Trig'd" (Triggered) should momentarily appear above the graticule and the u_{GS} voltage waveform should be displayed. If this does not happen, ask the teacher to check oscilloscope settings.
11. Adjust (generating a switching pulse train 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_{GS} voltage is visible in its entirety (cf. Fig. 5) and occupies most of the screen horizontally.
12. Using the 2 button, display the waveform from channel 2, i.e. the u_{DS} voltage. Check whether the waveform is correct (see Fig. 5).

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.

13. 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).
14. Using the 4 button, display the waveform from channel 4 (its current shape being unimportant for now).
15. 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;

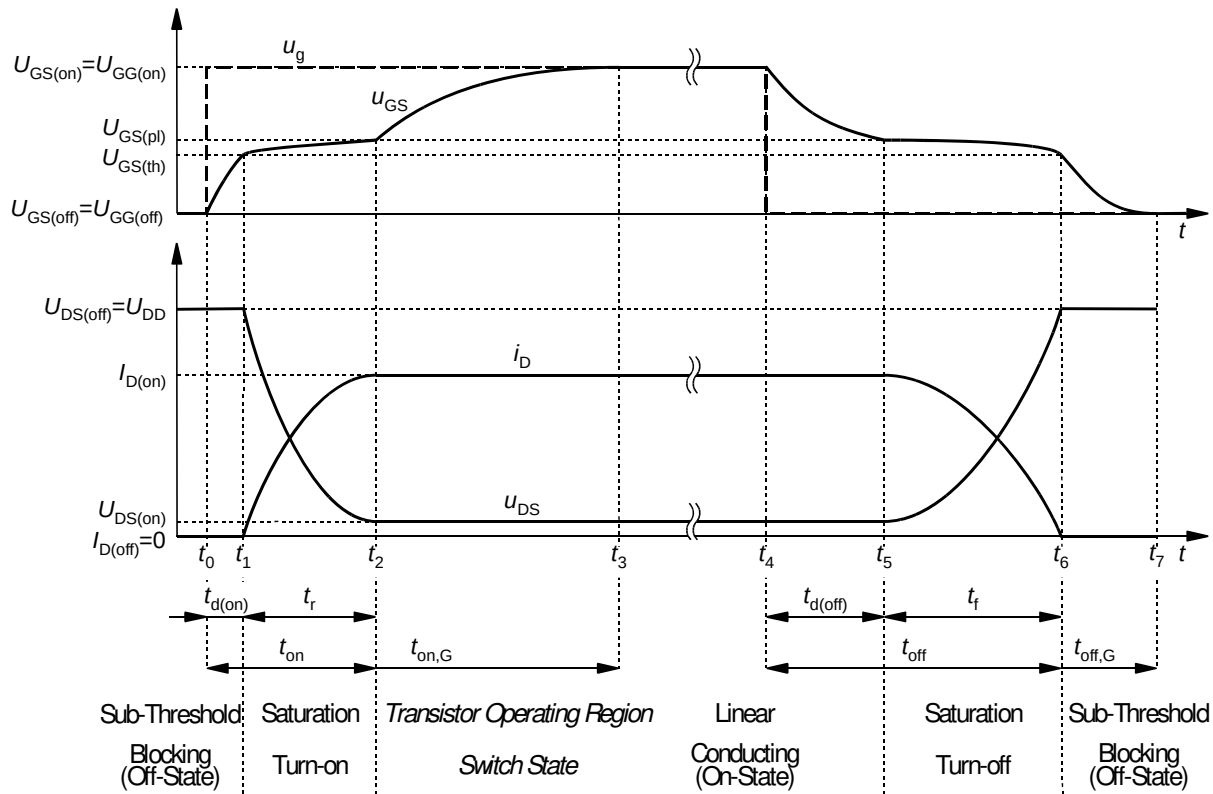


Fig. 5. Voltage and current waveforms during MOSFET switching

- initially set the current/voltage conversion ratio to a value enabling a current waveform with the amplitude I_o determined in step 3 to be measured and displayed on the oscilloscope (see information about current probe amplifier operation given in the current probe manual).

16. Set DC coupling on the current probe amplifier.

17. Clamp the probe around the appropriate wire fragment so that the drain current i_D 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).

18. Generating switching pulse trains, 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. 5).

19. 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:

- 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;
- temporarily hide the waveforms from channels 1 and 2;
- using the *Manual Balance* \uparrow/\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.

20. Generate a switching pulse train. Check if the current pulse amplitude observed on the oscilloscope is approximately equal to the value determined in step 3. 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!

3.4. 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. Record a complete set of the three waveforms, u_{GS} , u_{DS} and i_D (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

3. Record waveforms that will enable the transistor's turn-on state (not any other operating state) to be analysed:
 - (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, starting at the beginning of transition in the control circuit and up to waveforms settling in the power loop, i.e. all along the t_{on} interval (see Fig. 5);
 - (b) make sure that channel settings are still conforming to the requirements given in step 1, but this time including any possible overvoltages; if not, modify these settings according to step 1;
 - (c) record a complete set of the three waveforms, u_{GS} , u_{DS} and i_D (all together), in a graphical form;
 - (d) apart from that, download and save the same complete set of waveforms in a numerical form:
 - in the OpenChoice Desktop application, go to the *Waveform Data Capture* tab,
 - click *Select Channels* and tick channels CH1, CH2 and CH4,
 - 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.

4. Record waveforms that will enable the transistor's turn-off state to be analysed:
 - (a) before taking any other action, switch the oscilloscope to falling-edge triggering with the u_{GS} 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.

- (b) repeat step 3 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 3(d)], 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. 5.

In most cases, failure to carry out sub-step 3(a) will make it impossible during result elaboration to obtain required results from the image recorded.

Gate circuit at a zero drain-source voltage

5. * Restore the time base that enables a full switching cycle to be observed.
6. * Bring the U_{DD} voltage to zero (do not switch the power supply off).
7. * Change the triggering edge to the rising one (*Trigger Menu, Slope: \uparrow*). Do not modify any other oscilloscope settings, in particular, the time base or channel gains.
8. * Record the voltage waveforms only (i.e. u_{GS} and u_{DS}), in a graphical form.

Concluding measurements

9. Bring the power loop supply voltage down to zero. Wait until the red LED indicator goes out on the circuit's panel.
10. Bring the control circuit supply voltage down to zero.
11. 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.
12. Dismount the load resistor and the transistor. Tighten back all screws in the now unoccupied terminal block.

4. Processing and Analysing Results

4.1. Transistor as a switch and static state parameters

Switching cycle

1. Fill in Part 1 of the report.

Drain-source resistance and threshold voltage

2. Fill in Part 2 of the report.

Transistor as a switch in its static states

3. Fill in Part 3 of the report.

Operation in dynamic states

4. Fill in Part 4 of the report.

4.2. Operating point trajectory

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');
```

Plotting operating point trajectory and power loss

4. Read in data recorded in the numerical form (CSV format) for the transistor's turn-on state by executing the command:

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

5. To make result processing easier, create two variables and assign to them indices of the recorded waveforms of the drain-source voltage u_{DS} and the drain current i_D , by executing the commands:

```
iUds=oscwfmidx(OscRecord, 'channel_label_uds')
iId=oscwfmidx(OscRecord, 'channel_label_id')
```

The parameters *channel_label_uds* and *channel_label_id* represent labels of oscilloscope channels where the u_{DS} and i_D waveforms were measured, respectively. If probes were connected in accordance with this manual (steps 3.3/5 and 15), then these were channels 2 and 4 which the oscilloscope used labels as *CH2* and *CH4*. 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.

Handles to the two resulting sub-plots will be kept in the variables *axtrj* and *axpwr*, which will enable further curves to be added there.

6. Read in the file *out_irf540n_20a_80v.csv*, which contains data representing the static output characteristic of the transistor investigated, by executing the command:

```
TrcRecordOut=trcreadcsv('out_irf540n_20a_80v.csv');
```

7. Obtain a graph of the trajectory of the transistor's operating point (u_{DS} , i_D) against the output characteristics $I_D = f(U_{DS})$ in the background, together with the corresponding power loss in the drain circuit $p_D = u_{DS} i_D = f(U_{DS})$:

```
[axtrj, axpwr]= plot3p_outtrjpwr(OscRecord, iUds, iId, TrcRecordOut)
```

The variables *axtri* and *axpwr* will store handles for particular subplots, which will enable a load line to be added in the future.

8. Using the known parameters of the experimental circuit (see steps 3.3/3 and 3.3/4), calculate the parameters of a theoretical, straight load line for a resistive load (see Ref. D): the coordinates of the point of intersection with the current axis I_0 and of the point of intersection with the voltage axis U_0 .
9. Add the load line to the operating point trajectory sub-plot, which is equivalent to plotting a straight line between the points (0; I_0) and (U_0 ; 0) by executing the command:

```
plot(axtrj, [0 U0], [I0 0])
```


where the symbols U_0 and I_0 are to be replaced with the values calculated in step 8.

10. Determine whether both ends of the load line correspond to the calculated points of intersection and whether they approximately correspond to the extreme points of the operating point trajectory. If not, determine and eliminate the source of the discrepancy (e.g. incorrect command execution, numerical values used not in accordance with the reality, incorrect calculations, incorrect scale settings of the oscilloscope).
11. Using any appropriate software, label visible transistor operating regions in the graph (see Ref. [13]).
12. Paste the graph obtained in the appropriate space provided in Part 5 of the report.
13. Repeat steps 4 to 12 for the turn-off state, but this time skipping step 8.

Result analysis

14. Fill in Part 5 of the report.

5. Required Knowledge

5.1. Prerequisites

- Power MOSFET control and main (power) terminals (Ref. A)
- Field-effect control principle, turn-on conditions (Refs. A, B and C)
- Voltage and current waveforms during MOSFET switching under resistive load (Ref. D)

5.2. Test scope

1. Semiconductor switch. Static and dynamic (switching) operating states. Ideal and real (practical) switch and their principal characteristics. The quantity—voltage or current—considered as the cause (applied to the switch) and the one considered as the result in either static state. (Manual 0, Ref. G)
2. Field-effect control: channel formation (without formulae or physical details), static (voltage-related) and dynamic (capacitance-related) conditions for turn-on. (Refs. A and B)
3. VDMOS parasitic capacitances: location in the equivalent schematic, location within the semiconductor structure, physical interpretation (without formulae), dependence on the U_{DS} voltage (graph). (Ref. B; Manual 0, Ref. H)
4. Voltage and current waveforms during VDMOS switching under resistive load. Steady-state values and their relation to circuit parameters. Operating point trajectory in the output static characteristics plane. Operating states and regions of operation in output static characteristics and along time waveforms. Effect of parasitic capacitances: the RC model of the transistor's control circuit, input capacitance, Miller capacitance (formulae). (Fig. 5; Ref. C considering the purely resistive load case; Ref. D; report)
5. Drain power loss depending on operating point. Effect of stray inductance on operating point trajectory and power loss under a real (practical) resistive load. (Ref. D; Manual 0, Ref. G, Fig. 6.3(b); report)

6. References

- [1] Benda V., Gowar J., Grant D. A.: *Power Semiconductor Devices: Theory and Applications*. Wiley, 1999. ISBN 0-471-97644-X.
- [2] Williams B. W.: *Principles and Elements of Power Electronics: Devices, Drivers, Applications, and Passive Components*. Barry W Williams, 2006. ISBN 978-0-9553384-0-3.
- [13] Oh K. S.: *MOSFET Basics*. Rev. D. Fairchild, July, 2000. Application Note AN9010.