**Politechnika Łódzka**
**Katedra Mikroelektroniki i Technik Informatycznych**
90-924 Łódź, ul. Wólczańska 221/223, bud. B18
tel. 42 631 26 28 faks 42 636 03 27 e-mail secretary@dmcs.p.lodz.pl
http://www.dmcs.p.lodz.pl

POWER DEVICES AND SYSTEMS LABORATORY

# Exercise 6P

## Power Loss under Switched-Mode Operation

Low-Side Switch
Computer Simulation of Switched-Mode Power Converters

Exercise and manual elaborated by
Łukasz Starzak

Łódź 2019

ver. 7.2.0. 18/10/2019

## Contents

# B

# Exercise Introduction

## 1. Exercise Aim and Plan

The aim of this exercise is to investigate the different components of power loss in a semiconductor switch including their variations with switching frequency. This also creates an opportunity to use computer simulation for analysing the operation of power semiconductor devices and circuits.

The abovementioned problem will be analysed based on a specific device example: the MOSFET. Thanks to its operation being relatively simple, it will not be necessary to consider any secondary phenomena. The transistor will operate in its simplest circuit configuration: the low-side switch; it will be used to realise the function of the simplest power electronic converter: a DC voltage chopper.

# 2. Power Loss in MOSFETs

## 2.1. Recommended reading

| Ref. | Textbook | Excerpt | Equivalent in the Polish Manual | Complementary Reading | Complements in this Manual |
|---|---|---|---|---|---|
| A* | Ben | 10.3.3 | 2.1 | | |
| B** | Wil | 6.3, 6.3.1, 6.3.2, 6.3.3 | 2.3.d | | |
| | | | 2.3.e | | 2.2 |

* Ref. A is found in the document already published as Refs. ABC for Manual 3P.

** Ref. B is found in the document already published as Ref. D for Manual 3P.

Additionally, from Manual 3P references:

| Ref. | Textbook | Excerpt | Equivalent in the Polish Manual | Complementary Reading | Complements in this Manual |
|---|---|---|---|---|---|
| 3P A | Ben | 10.2.1 | 2.2 | [13] 6.3 | |
| 3P D | Wil | 6, 6.1, 6.1.1, 6.1.2 | 2.3.a—c | | |

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.

## 2.2. Practical measurement of dynamic energy dissipation

If we consider only the drain circuit, measuring the energy dissipated in a MOSFET in dynamic states always requires recording $i_D$ and $u_{DS}$ waveforms, their multiplication and integration:

$$W_{D(on)} = \int_{t_{inf(on)}}^{t_{sup(on)}} p_D \, dt = \int_{t_{inf(on)}}^{t_{sup(on)}} i_D u_{DS} \, dt \tag{2.1}$$

$$W_{D(off)} = \int_{t_{inf(off)}}^{t_{sup(off)}} p_D \, dt = \int_{t_{inf(off)}}^{t_{sup(off)}} i_D u_{DS} \, dt \tag{2.2}$$

where $t_{inf(on)}$ and $t_{sup(on)}$, and $t_{inf(off)}$ and $t_{sup(off)}$ are the integration limits.[1]

To enable practical measurements and, at the same time, result standardisation, the integration limits are determined based on characteristic relative values of relevant waveforms, as in the case of determining time-related parameters (see Manual 3P, Section 2.2). According to international standard IEC 60747-8-4, when energy is concerned, the $t_{inf}$ and $t_{sup}$ moments are defined by the relative values of 10% of the $i_D$ and $u_{DS}$ waveforms, as illustrated in Fig. 1.

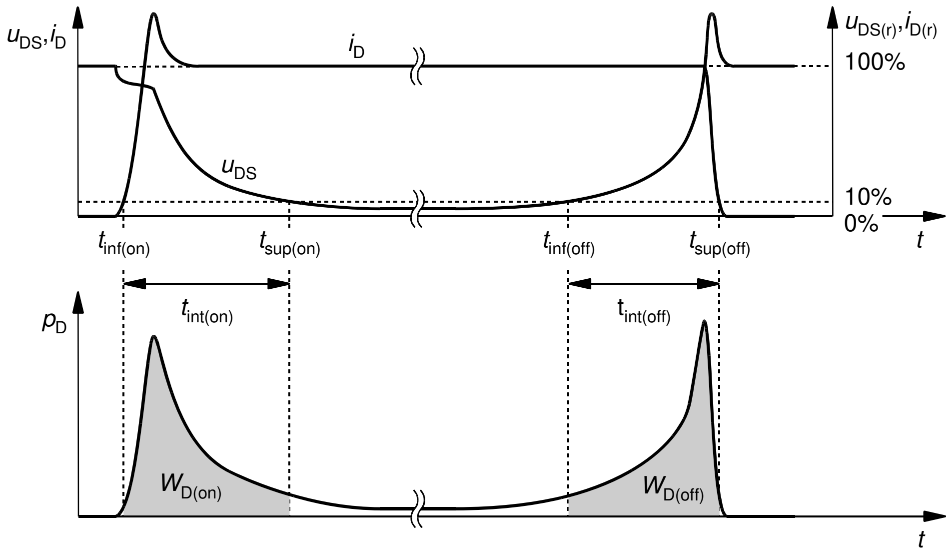


*Fig. 1. Method for determining energy-related parameters of the MOSFET according to IEC 60747-8-4*

Inductive load is the most characteristic for devices operating in power electronic converters as well as because it involves highest power losses. Therefore, the standard requires this type of load to be used when measuring energy-related parameters of MOSFETs.

---

[1] In the case of macroscopic characterization of power semiconductor devices, the symbol $E$ has been customarily adopted (also in the standard) for energy dissipation. However, in accordance with references and the majority of scientific publications and textbooks, we will use the symbol $W$. This is for two reasons: 1° to distinguish energy from electric field and 2° for consistency with reference chapters on energy bands and energy transfer in power conversion systems.

# 3. DC Voltage Chopper

## 3.1. Pulse wave-based control

### 3.1.a. Pulse wave

As opposed to linear-mode circuits, in switched-mode ones, the semiconductor device is fully on (with the lowest voltage drop possible across it) for some time interval and it its fully off (will a virtually zero current flow) for the rest of the time. Thanks to this approach, power loss is greatly reduced. To achieve such an operation mode, a suitable control is necessary, where the control signal is not time-continuous, but changes abruptly.

In pulse wave-based control, a controlling quantity $x$ (current or voltage) takes the form of a pulse wave. It consists of periodically repeated pulses, i.e. sections of a level higher than the idle one, whose shape, to simplify, can be considered rectangular [see Fig. 2(a)].

A pulse wave is described by the following parameters:

(1) ***repetition period*** $T_\mathrm{p}$ which is the shortest time interval after which values of the considered quantity repeat; therefore, it is e.g. the interval between the beginnings of successive pulses;

(2) ***repetition frequency*** $f_\mathrm{p}$ which is the inverse of the repetition period:

$$f_\mathrm{p} = \frac{1}{T_\mathrm{p}} \tag{3.1}$$

(3) ***pulse width*** $t_\mathrm{p}$ which is the duration of the top of the pulse;

(4) ***duty cycle*** (also called *duty ratio*) $D$ which is the ratio of the pulse width to the repetition period:

$$D \overset{\Delta}{=} \frac{t_\mathrm{p}}{T_\mathrm{p}} \tag{3.2}$$

As it can be easily seen, just one of the parameters 1 or 2 and one of the parameters 3 or 4 are sufficient for an unambiguous description of a pulse wave in the time domain.

In the domain of the electrical quantity considered (current or voltage), a pulse wave is described by:

(5) ***low level*** $X_\mathrm{L}$ which is the value of the quantity $x$ corresponding to the base of the pulse;

(6) ***high level*** $X_\mathrm{H}$ which is the value of the quantity $x$ corresponding to the top of the pulse;

(7) ***amplitude*** $X_m$ which is the distance between the low and the high levels

$$X_m = X_H - X_L \tag{3.3}$$

As it can be easily seen, any two of the parameters 5 to 7 are sufficient for an unambiguous description of a pulse wave.

In power electronics, waveforms with a zero base level ($X_L = 0$) can often be seen, for which $X_H = X_m$. Because of the prevalence of this case and due to the considerable simplification of relationships that are obtained, it is usually the zero base level that is assumed in analysis.

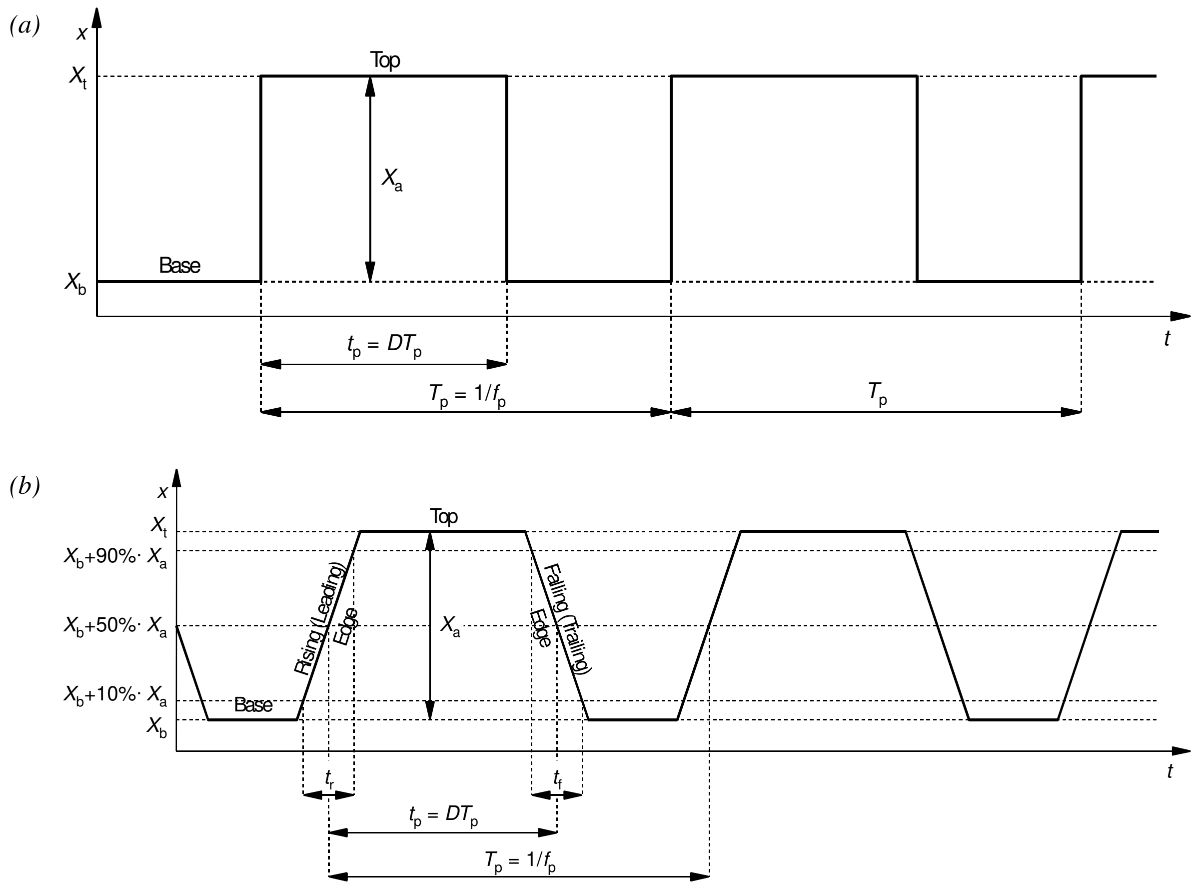


*Fig. 2. Pulse wave and its basic parameters: (a) the ideal waveform; (b) a waveform with finite edge steepness*

### 3.1.b. Parameters of a real pulse wave

The abovementioned parameters fully describe only ideal pulses, which cannot be generated in practice. For example, the non-zero edge duration is one of the features of a real pulse wave. The edges are additionally described by [see Fig. 2(b)]:

(8) ***rise time*** $t_r$, i.e. the time it takes for the waveform to rise from 10% to 90% of its amplitude, which is a measure of the duration of the rising edge (also called the leading edge);

(9) ***fall time*** $t_f$, i.e. the time it takes for the waveform to fall from 90% to 10% of its amplitude, which is a measure of the duration of the falling edge (also called the trailing edge).

If the above times are shorter than the shortest pulse width in a given circuit, then their effect on its behaviour can be neglected.

A more detailed analysis or design of pulse wave-controlled power converters may require considering additional factors such as overshoots, settling time, frequency or phase jitter. They can negatively affect circuit operation.

## 3.2. Single transistor switch as a DC/DC power converter

### 3.2.a. Low-side switch

The simplest configuration of a transistor switch is the low-side switch. Using this topology, a DC voltage chopper can be realised, which is the simplest pulse wave-controlled DC/DC power electronic converter. Its schematic is presented in Fig. 3.

The term “low-side” indicates how the semiconductor switch (the transistor Q in Fig. 3) is located with respect to the load (the resistor $R_L$ in Fig. 3). In this configuration, the switch is found on the side of the lower potential (negative terminal) of the source $U_{DD}$. In the opposite case, when the switch is located on the side of the higher potential (positive terminal) of the source, the configuration is called “high-side switch.”

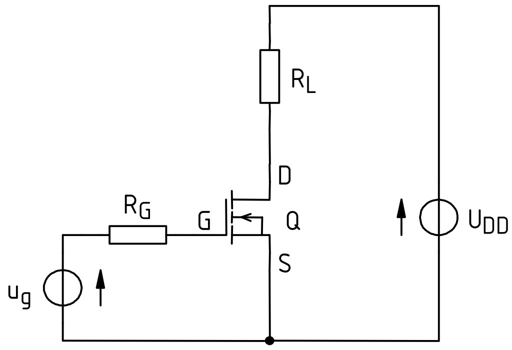


*Fig. 3. The schematic of the low-side switch circuit to be used in simulations*

On the other hand, the term “chopper” refers to the function fulfilled by the considered circuit from the point of view of electric power conversion. This function is to periodically remove power supply from the load, thus causing the voltage waveform across the load (receiver) to appear as “chopped.” The transistor’s operating state changes according to the controlling 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. Assuming that the transistor is an ideal switch, it represents a short-circuit, so the full supply voltage $U_{DD}$ is applied to the receiver $R_L$ (see Fig. 4a);

(2) when the transistor is off, the resistance between its source and drain is high, which disables current flow in the power loop. Assuming that the transistor is an ideal switch, it represents a break in the circuit. As no current is flowing, the voltage across the $R_L$ resistor is zero (see Fig. 4b).

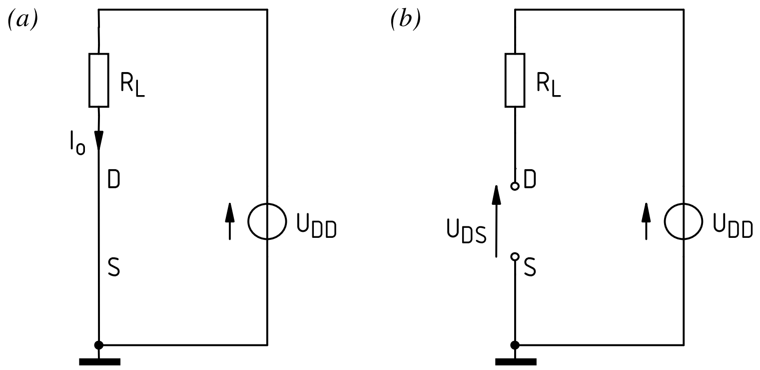


*Fig. 4. Power loop of the chopper circuit for an ideal semiconductor switch: (a) in the on-state; (b) in the off-state*

### 3.2.b. Chopper as a DC/DC converter

Any change in the duty cycle $D$ of the $u_g$ waveform entails a change of the time interval length when the transistor is on. As a result, the average value of the output voltage (across the load) $u_o$:

$$U_{o(av)} = \frac{1}{T_p}\int_0^{T_p} u_o \mathrm{d}t = \frac{1}{T_p}\left(\int_0^{t_p} u_o \mathrm{d}t + \int_{t_p}^{T_p} u_o \mathrm{d}t\right) = \frac{1}{T_p}\left(\int_0^{t_p} U_{DD} \mathrm{d}t + \int_{t_p}^{T_p} 0 \,\mathrm{d}t\right) = \frac{1}{T_p}\left(U_{DD}\int_0^{t_p} \mathrm{d}t + 0\right) = \\ = \frac{1}{T_p} U_{DD} t_p = D U_{DD} \tag{3.4}$$

Considering that the duty cycle takes values from the range of [0; 1], the considered circuit realises the function of lowering the average value of the output voltage. As the average value is equal to the direct component of a signal, this circuit can therefore be classified as a DC/DC power converter. However, it is so simple that it does not include an output filter. Consequently, in this case, the output voltage $u_o$ takes a pulse form instead of a constant one (not even approximately).

Electric power conversion is characterised by the average power (see Manual 0, Ref. C). According to its definition and based on the analysis results from Section 3.2.a, for a DC voltage chopper this power equals

$$P_o = \frac{1}{T_p}\int_0^{T_p} p_o \mathrm{d}t = \frac{1}{T_p}\int_0^{T_p} u_o i_o \mathrm{d}t = \frac{1}{T_p}\left(\int_0^{t_p} U_{DD}\frac{U_{DD}}{R_L} \mathrm{d}t + \int_{t_p}^{T_p} 0 \,\mathrm{d}t\right) = \frac{1}{T_p}\frac{U_{DD}^2}{R_L}\int_0^{t_p} \mathrm{d}t = \\ = \frac{1}{T_p}\frac{U_{DD}^2}{R_L} t_p = D\frac{U_{DD}^2}{R_L} \tag{3.5}$$

Similar to the direct component of the output voltage, the output power is a linear function of the duty cycle. Therefore, by varying the duty cycle, it is possible to regulate the average value of the voltage supplying the load and thus, the average power supplied to the load. This proves that the analysed circuit indeed fulfils the task of a power converter.

# C

# Experiment

## 4. Simulations

### 4.1. Completing the schematic and configuring simulation

#### Circuit under analysis

A schematic of the circuit to be investigated by simulations is presented in Fig. 5. The gate resistor $R_G$ has a value of 100 Ω; this value is relatively high and has been chosen to emphasise effects observed. Other components' values are determined for each team individually.

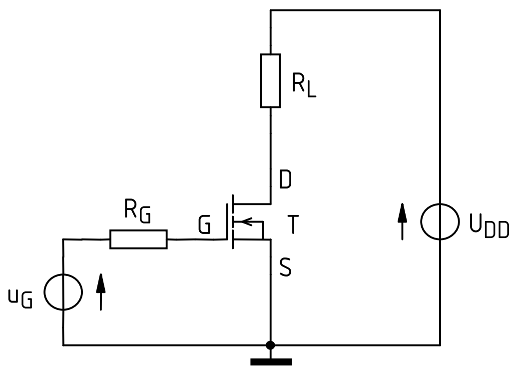


*Fig. 5. The schematic of the low-side switch circuit to be used in simulations*

A model of the IRF620 component will be used for the transistor Q. This model comes in two variants, corresponding to different operating temperatures: the standard room temperature of 25 °C and the maximum rated one (for the considered transistor) of 150 °C. These two models have been differentiated by the suffix "_*x*C" added to the designation, where *x* is a temperature value in degrees Celsius.

The pulse wave source $u_g$ is to represent a real control circuit in the form of an integrated gate driver, IR2117, whose data sheet is attached to this manual. For simplicity, in this exercise it will be assumed that the driver's output resistance is zero, thus its output voltage toggles between the level of 0 V and the supply voltage of the control circuit. In order to drive the gate of the transistor Q properly, a value of 15 V will be used for the latter. The control waveform frequency is established individually whereas its duty cycle should be set at 0.5.

### Sources and passive components

1. In the MicroSim environment, create a new project containing a preliminary circuit schematic:
   (a) from the *Start* ‣ *Projektowanie* menu, launch Design Manager from the MicroSim 8 package;
   (b) in the Design Manager window, create a folder for the new project:
      - select *File* ‣ *Workspace* from the menu,
      - in the *Location* field, enter or select (using the "…" button) the path for a folder (conforming to laboratory regulations) where the project is to be created,
      - click *Create*;
   (c) copy the file *lacznik_dolny.sch*, which contains a schematic corresponding to the circuit of Fig. 5, to the project folder created;
   (d) in the project window in Design Manager, unfold the *Schematics* list and double-click the file just copied, which should cause it to be opened in the Schematics application.
2. Modify names of all circuit components by changing the characters "??" to your team number (e.g. UG99).

   **Results obtained in circuits with unsuitable component names will be considered as cheated.**

3. From the web page, obtain initial values for switching frequency $f_{s,ini}$, power loop supply voltage $U_{DD}$ and on-state drain current $I_{D(on)}$.
4. Based on appropriate values from step 3 and representing the transistor with an ideal switch (see Section 3.2.a), calculate a load resistance $R_L$ such that when the power loop is supplied with a voltage of $U_{DD}$, the on-state drain current equals $I_{D(on)}$.
5. Based on appropriate data, complete the schematic with component parameters:
   (a) after double-clicking the symbols "?" located by the respective components, enter the values for $R_G$, $U_{DD}$ and $R_L$ (see steps 3 and 4);
   (b) double-click the $u_G$ source symbol and enter the parameters of the control waveform:

   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. Units or their prefixes must not be separated with spaces from numbers.

   The simulators of the SPICE family have their own circuit description language where dot is the decimal sign (so comma is not). This format applies to any application within the MicroSim package, independent on operating system settings.

      - *PER* for period $T_p$, which should be calculated using the known frequency $f_{s,ini}$ (see step 3),
      - *PW* for pulse width $t_p$, which should be calculated using the known frequency $f_{s,ini}$ and duty cycle $D$ (see step 3, the description of the circuit under analysis above and Section 3.1.a),
      - *TD* for delay time, equal 0,
      - *TR* for rise time $t_r$, equal to the rise time $t_r$ of the output signal of the gate driver specified above, according to its data sheet (use the typical value, i.e. the one listed in the *typ* column),
      - *TF* for fall time $t_f$, equal to the fall time of the output signal of the gate driver (by analogy to *TR*),
      - *V1* for the low level $U_L$, equal 0 V (a value typically used to turn off a transistor),

- *V2* for the high level $U_H$, equal 15 V (a value that ensures the transistor will turn on with a low $u_{DS}$ voltage drop).

6. Insert the transistor into the circuit (menu *Draw* ‣ *Get New Part*, or *Ctrl+G*), using the model variant for the junction temperature of 25 °C; name it according to the guideline given in step 2.

### Starting the simulation

MicroSim and Probe manuals available at the laboratory stand may be helpful in performing simulations.

7. Define simulation parameters:
   (a) open the *Analysis Setup* dialog using the *Setup Analysis* icon (or by selecting *Analysis*‣ *Setup* from the menu);
   (b) select transient analysis only by checking the selection box next to the *Transient* button and unchecking all the other boxes;
   (c) click the *Transient* button and set:
   - *Final Time*, which is the time when simulation is finished, such that periodic operation of the circuit with the frequency obtained in step 4.1/3 can be observed,
   - *Print Step*, which is the step of dumping results to a text file, should be as large as possible to speed up the simulation as this text file will not be used, however, it cannot be lower than *Final Time*,
   - *Step Ceiling*, which is the upper limit for the simulation step (the distance between subsequent time points), to 5 ns (approximately 1/5 of the transistor's switching times), which will enable a sufficiently high waveform resolution to be obtained in dynamic states while keeping the computation time acceptable;

   (d) close the *Transient* and *Analysis Setup* dialogs;
   (e) select *Analysis* ‣ *Probe Setup* from the menu and enable:
   - running the Probe application automatically after simulation is completed (*Automatically run Probe after simulation*),
   - displaying waveforms marked in the schematic (*Show all markers*).

8. Place a current marker (the *Current Marker* icon or *Markers* ‣ *Mark Current into Pin* menu item) so that to measure the transistor's drain current.

The power MOSFET model used has the form of a sub-circuit. For this reason, it is impossible to apply a current marker to any of its graphical symbol's terminals Therefore, the drain current must be measured in any other component of the circuit where, according to the schematic, this current also flows.

If the *Add Trace* function is used in Probe, no quantities from inside the transistor model sub-circuit should be plotted; these can be recognized by the letter "X" in their names. They can be hidden in the *Add Trace* dialog by unchecking the *Subcircuit Nodes* option. Even though quantities named ID, IG etc. appear among them, these are currents of a transistor that is just one part of the model and whose currents are not identical with terminal currents of the power MOSFET under investigation.

9. Perform a preliminary simulation of the circuit:
   (a) start the simulation with the *Simulate icon* (or by selecting *Analysis* ‣ *Simulate* from the menu, or by pressing *F11*); the PSpice A/D application should be opened;
   (b) in case of any error, determine and eliminate its cause using the manual for the MicroSim environment;

   after the simulation successfully completes, the Probe application should be launched and the transistor's drain current waveform should be displayed;

   (c) check if the final simulation time has been chosen adequately [see step 7(c)]; if not, modify simulation settings as appropriate and re-run the simulation;
   (d) if the sign of the current is incorrect, obtain a correct result according to the remark below.

It follows from the topology of the power loop and from Kirchhoff's voltage law that the transistor's drain current is positive following the arrows convention adopted in electrical engineering. If the sign of the current displayed in Probe is negative, then this is just a result of the marker being applied in Schematic to a terminal whose current has a conventional direction opposite to the true drain current in the circuit. A user does not have any influence on the way voltages and currents are assigned their directions by the simulator; this is predefined in component models and symbols with no relation to a particular circuit. In such a case, the waveform should be corrected by moving the current marker to the other terminal of the component in Schematics (re-running the simulation is unnecessary provided the MicroSim package is correctly installed and operated) or by adding a minus sign ("-") in the waveform definition in Probe after double-clicking its label under the plot.

10. Add voltage waveforms to the plot:
    (a) create an additional Y-axis by selecting *Plot ‣ Add Y Axis* from the menu; the new axis 2 should be marked as the active one with a ">>" sign; if not, click the axis to select it;
    (b) by adding voltage markers in Schematics (*Voltage/Level Marker* icon or menu item *Markers ‣ Mark Voltage/Level*), plot the following against axis 2: dran-to-source voltage $u_{DS}$, control voltage $u_g$ and gate-to-source voltage $u_{GS}$;

    In this specific case, it is possible to use simple voltage markers, because according to the circuit schematic, the reference potential for each of the above voltages is zero; otherwise voltage differential markers would have to be used (menu item *Markers ‣ Mark Voltage Differential*).

    (c) determine whether the waveforms shown are proper for the switch-mode operation of a transistor as well as whether transistor control and switching occur with the frequency and duty cycle used in step 4.1/5(b); if not, check if the circuit parameters entered are correct and if the transistor's model has been properly selected.

    If simulation has to be repeated, it is possible to restore the previous view (i.e. axis and waveform layout) in Probe by selecting *Tools ‣ Display Control* from the menu and double-clicking the *Last Session* item, or alternatively, by pressing *F12*.

## 4.2. Power loss and effect of switching frequency

### Instantaneous power loss in the transistor

1. Add a new sub-plot containing the instantaneous drain power loss waveform:
   (a) create a second sub-plot (*Plot ‣ Add Plot* from the menu); the new sub-plot should be marked as the active one with a "SEL" label; if not, click anywhere inside the sub-plot to select it;
   (b) copy the drain current waveform $i_D$ from the lower sub-plot to the upper one by selecting it with a click on its label below the graph (the label should become highlighted in a different colour) and then invoking the *Copy* and *Paste* functions using the menu, appropriate icons or keyboard;
   (c) double-click the label of the copied waveform (below the upper sub-plot) and modify its defining mathematical expression (*Trace Expression*) so that it represents the transistor's drain power loss $p_D$ (see Section 2.2 or Ref. A); for quantities other than $i_D$, appropriate designations that Probe can understand should be read out from waveform labels below the lower sub-plot;

   note that, the transistor being a dissipative (as opposed to generating or storing) component, the curve obtained must exhibit positive values [if this is not the case, see the remark under step 4.1/9(d)].

   If a formula involves a combination of the multiplication sign and the minus sign, the expression that contains the minus sign must be enclosed between parentheses; otherwise a calculation error may arise which will make the application close.

2. To prevent an accidental loss of work results related to plot configuration, save present view settings (i.e. sub-plot, axis and waveform settings) by selecting *Tools ‣ Display Control* from the menu, providing a name for the view in the *New Name* field and clicking *Save*.

   To later restore the saved view settings, select the respective view name from the list and click *Restore*.

3. From the plot, read out peak instantaneous power loss $p_{D(pk)}$ in each of the operating states of the transistor
   (a) using the *View Area* function (an icon in the toolbar, or *View* menu), zoom in the time scale so that to observe the transistor's turn-on state (cf. Fig. 6):

   The *View In* function should not be used for zooming waveforms in this exercise. This is because waveforms will have to be zoomed mostly in the time axis and much less so (or not at all) in the Y-axis, while the *View In* function scales both axes at an identical ratio.

   The *View Area* function should best be used in the current and voltage sub-plot (as opposed to the power and energy sub-plot). This is because this way, power and energy scales will be automatically adjusted to their respective ranges within the magnified time interval.

   (b) activate cursors using the *Toggle cursor* icon (or by selecting *Tools ‣ Cursor ‣ Display* from the menu);
   (c) move cursor 1 to the instantaneous power waveform $p_D$ by clicking the graphical symbol left of the respective waveform label below the appropriate sub-plot, which should result in a frame appearing around the symbol;
   (d) using the *View Area* (to zoom in) or *View Fit* (to zoom out) functions, with the cursor, read out (see Fig. 7) the peak value of the instantaneous power loss $p_{D(pk)}$ (cf. Fig. 6) in each of the transistor's four operating states (i.e. turn-on, conducting, turn-off and blocking), while considering the following:
      - the first two switching periods should be ignored as the simulated circuit might not reach its steady state yet;

- the operating state should be determined based on the observation of the drain current waveform $i_D$;
- by definition, in static states, the power does not change, so the peak value is identical to the constant value of power in these states;
- because a small variation of the power value in static states is observed in reality, make your readouts always in the middle of the time interval corresponding to the static state under consideration (see Fig. 6).

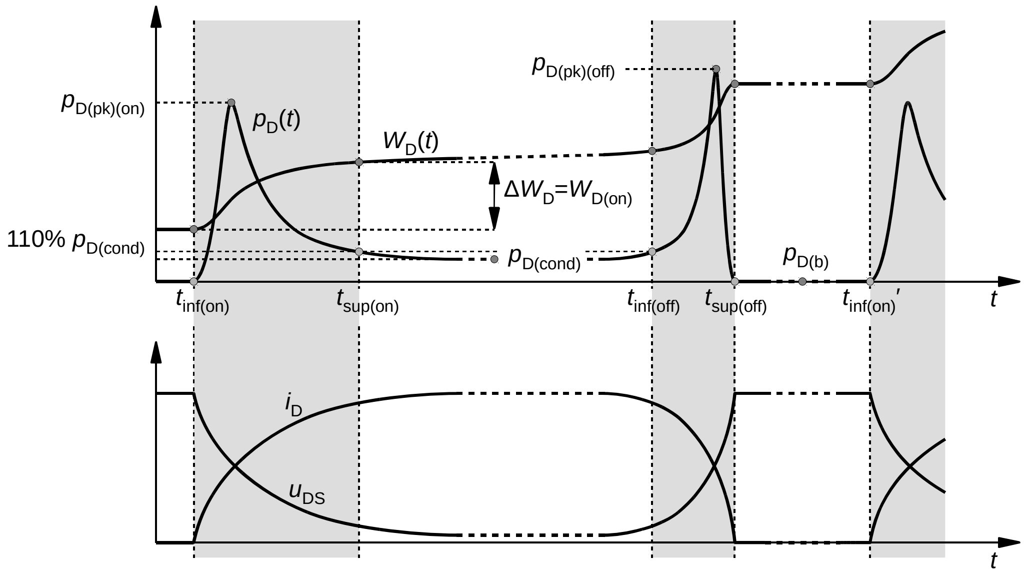


*Fig. 6. Readout example of peak instantaneous power loss $p_{D(pk)}$ and of energy dissipation $W_D$ in the different operating states*

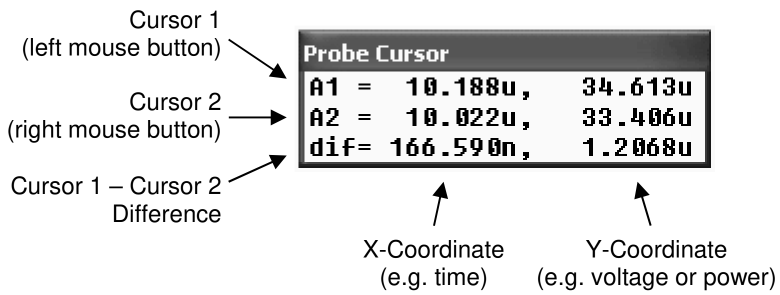


*Fig. 7. Interpretation of values displayed in the Probe Cursor floating window*

## Energy dissipation in the transistor

4. Additionally display a waveform for the energy dissipated in the transistor:
   (a) in the upper sub-plot, create a second Y-axis and make sure it is the active one [see steps 4.1/10(a) and 4.2/1(a)];
   (b) copy the instantaneous power waveform $p_D$ from axis 1 to axis 2 by selecting it with a click on its label below the graph and then using the *Copy* and *Paste* functions;
   (c) double-click the label of the copied waveform and modify its defining mathematical expression so that it represents the energy $W_D(t)$ dissipated in the transistor's drain circuit from zero time to a time of $t$ (cf. Section 2.2):

$$W_D(t) = \int_0^t p_D(\tau)\mathrm{d}\tau \qquad (4.1)$$

where $\tau$ is an auxiliary integration variable which for each time point $t$ sweeps the time axis in the range of 0 to $t$.

For the purpose of calculating an integral of this kind, the function S() can be used in Probe, defined as:

$$\mathrm{S}(g) = f(t) = \int_0^t g(\tau)\mathrm{d}\tau \tag{4.2}$$

where $g$ can be any expression involving quantities available in Probe.

5. Restore default axis scales with the *View Fit* icon or by selecting *View* ‣ *Fit* from the menu. Next, save the present view settings (see step 2).
6. Save the graph with at least one full switching period of the transistor visible: choose *Tools* ‣ *Copy to Clipboard* from the menu, then paste to a text document or to a graphics editor and save to a file.
7. Move cursor 1 to the energy waveform $W_D(t)$ [see step 3(c)]. Using the cursor (see Fig. 7), from the waveform, read out values of energy $W_D$ at the five time points corresponding to (see Fig. 6):
   - the beginning of the turn-on state $t_{inf(on)}$,
   - the end of the turn-on state $t_{sup(on)}$,
   - the beginning of the turn-off state $t_{inf(off)}$,
   - the end of the turn-off state $t_{sup(off)}$,
   - the end of the switching period, equivalent to the beginning of the turn-on state belonging to the next period $t_{inf(on)}'$,

   while considering the following (cf. Fig. 6):
   - the first two switching periods should be ignored for the reasons stated earlier;
   - all the abovementioned time points must belong to <u>a same</u> (single) switching period;
   - boundaries of dynamic states 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;
   - on the other hand, 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 110% of its steady on-state value $p_{D(cond)}$ as read out in step 3; to read out the value of power requested, you should:
     - temporarily move to cursor to the $p_D(t)$ waveform [see step 3(c)],
     - while observing the appropriate value in the *Probe Cursor* window, move the cursor to the time point at which the value of the instantaneous power $p_D$ attains the value of $100\% \times p_{D(cond)}$, at the end of the turn-on state or at the beginning of the of the turn-off state, as appropriate,
     - without moving the cursor in the plot, move it back to the $W_D(t)$ waveform [see step 3(c)],
     - from the *Probe Cursor* window, read out the value of energy $W_D(t)$;
   - results should be read out with the maximum accuracy (number of significant digits) available, so that to ensure that the accuracy of results obtained later by subtraction stays sufficient; subsequently, it will be possible to round those results of subtraction themselves;
   - while carrying out the present step, it is best to perform step 8 at appropriate moments.
8. Save waveforms with a magnified time scale for the turn-on state and for the turn-off state (two separate pictures).
9. Calculate the energies dissipated in the four different operating states of the transistor. The energy in question is the difference $\Delta W_D$ in the values of $W_D(t)$ between the time points corresponding to the beginning and the end of the considered operating state, according to formula (4.1):

- for the turn-on state (see Fig. 6):

$$W_{\mathrm{D(on)}} = \int_{t_{\mathrm{inf(on)}}}^{t_{\mathrm{sup(on)}}} p_{\mathrm{D}}(\tau)\mathrm{d}\tau = \int_{0}^{t_{\mathrm{sup(on)}}} p_{\mathrm{D}}(\tau)\mathrm{d}\tau - \int_{0}^{t_{\mathrm{inf(on)}}} p_{\mathrm{D}}(\tau)\mathrm{d}\tau = W_{\mathrm{D}}(t_{\mathrm{sup(on)}}) - W_{\mathrm{D}}(t_{\mathrm{inf(on)}}) = \Delta W_{\mathrm{D}} \qquad (4.3)$$

- for the conducting state:

$$W_{\mathrm{D(cond)}} = W_{\mathrm{D}}(t_{\mathrm{inf(off)}}) - W_{\mathrm{D}}(t_{\mathrm{sup(on)}}) \qquad (4.4)$$

- for the turn-off state:

$$W_{\mathrm{D(off)}} = W_{\mathrm{D}}(t_{\mathrm{sup(off)}}) - W_{\mathrm{D}}(t_{\mathrm{inf(off)}}) \qquad (4.5)$$

- and for the blocking state:

$$W_{\mathrm{D(b)}} = W_{\mathrm{D}}(t'_{\mathrm{inf(on)}}) - W_{\mathrm{D}}(t_{\mathrm{sup(off)}}) \qquad (4.6)$$

## Switching frequency variation

10. Modify the parameters of the $u_g$ [see step 4.1/5(b)] so that to obtain a switching frequency five times higher than the present one (i.e. $f_{\mathrm{s,ini}} \cdot 5$). All the other circuit parameters, <u>including</u> the control waveform <u>duty cycle</u> *D*, should remain unchanged, which makes it <u>necessary to modify an additional</u> parameter of the source.
11. Modify the simulation final time so that the periodic operation of the circuit can still be observed. All the other analysis parameters should remain unchanged.
12. Run the simulation. After it successfully completes, in Probe, restore the view settings saved in step 5 by selecting *Tools* ‣ *Display Control* from the menu, choosing an appropriate settings name and clicking *Restore*.

    If settings were correct at the end of the last simulation, then they can be restored without opening the *Display Control* dialog, just by pressing the *F12* key. It may be necessary to restore default axis scales.

13. Repeat step 3 and steps 6 to 9 to obtain values of power loss and energy dissipation in the transistor's four operating states for the modified switching frequency.
14. * Repeat steps 10 to 13 while applying a switching frequency five times lower than the <u>initial</u> (not the present) one (i.e. $f_{\mathrm{s,ini}} / 5$).

# D

# Results

## 5. Processing and Analysing Results

### 5.1. Power loss components

#### Electronic circuit components

1. Fill in Part 1 of the report.

#### Comparison of energy dissipation and power loss components

2. In Part 2 of the report, include the plots of the $u_g$, $u_{GS}$, $i_D$, $u_{DS}$, $p_D$ and $W_D$ waveforms obtained by simulation as saved in steps 4.2/6 and 8 for two (* three) different switching frequencies.
3. In a single in Part 2 of the report, gather the numerical results read out from waveforms in Probe for two (* three) different switching frequencies (leave the remaining table rows empty for now):
   - the energy dissipation in each of the four operating states $W_D$;
   - the peak value of the instantaneous power loss $p_{D(pk)}$ in each of the four operating states.
4. Calculate and add to the table (see Sub-chapters 2.2 and 3.1; Ref. A; and Manual 3P, Ref. D):
   - total energy dissipation over one switching period $W_{D(tot)}$, according to Eq. (10.58) in Ref. A, by summing the four components of the integral $W_D$ found in the result table;
   - switching period $T_s$;
   - total average power loss $P_D$, according to Eqs. (10.59) and (10.60) combined to yield:

$$P_D = f_p W_{D(tot)} = \frac{W_{D(tot)}}{T_p} \qquad (5.1)$$

- static average power loss $P_{\mathrm{D,stat}}$, which is the part of the total average power loss brought by the two static states, so:

$$P_{\mathrm{D,stat}} = \frac{W_{\mathrm{D(cond)}} + W_{\mathrm{D(b)}}}{T_{\mathrm{p}}} \tag{5.2}$$

- dynamic average power loss $P_{\mathrm{D,dyn}}$, which is the part of the total average power loss brought by the two dynamic states, so:

$$P_{\mathrm{D,dyn}} = \frac{W_{\mathrm{D(on)}} + W_{\mathrm{D(off)}}}{T_{\mathrm{p}}} \tag{5.3}$$

5. Complete Part 2 of the report.

## 5.2. Effect of switching frequency

### Effect of switching frequency on energy dissipation

1. Fill in Part 3 of the report.

### Effect of switching frequency on power loss

2. Fill in Part 4 of the report.

# E

# Information

## 6. Required Knowledge

### 6.1. Prerequisites

- Power MOSFET control and main (power) terminals
  (Manual 3P, Ref. A)
- Voltage and current waveforms during MOSFET switching under resistive load (including their characteristic values in the on-state and in the off-state)
  (Manual 3P, Ref. D)
- MOSFET (drain) power loss: instantaneous power formula and waveform over a switching period, on-state power loss, relation of energy to instantaneous power
  (Ref. A; Manual 3P, Ref. A, Section 10.2.1; Manual 3P, Ref. D)
- Pulse wave-based control and pulse wave parameters
  (Section 3.1)
- DC voltage chopper circuit topology and operation
  (Section 3.2)

### 6.2. Test scope

1. MOSFET (drain) power loss and energy dissipation: instantaneous power (formula), average power (formula), static (formula) and dynamic (formulae for the two types of load) components of the average power, energy dissipation (formula). MOSFET on-state resistance, effect of temperature, datasheet parameters. Instantaneous power and dissipated energy waveforms during transistor switching (juxtaposed with current and voltage waveforms).
   (Ref. A; Manual 3P, Refs. A, D and [13]; report)
2. Dependence of energy dissipation and average power loss on switching frequency: total values and contributions of the different operating states of a transistor considered as a semiconductor switch, with observations explained. Parameters important for transistor selection for a given circuit in respect of power loss minimisation depending on switching frequency.
   (report)

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

# 7. 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.