Transistor Switch and PWM

Student Group

First Name	Surname	Matrikel Nr.

Table of Contents

Transistor Switch and PWM

A transistor switch can connect and disconnect a load very quickly. If the switch is periodically on and off, the load sees an average voltage.

For an ideal switch with supply voltage \(U_{\rm dc}\):

\[\begin{align*} \overline{u}_{\rm L} = \frac{1}{T}\int_0^T u_{\rm L}(t)\,{\rm d}t = \frac{T_{\rm on}}{T}U_{\rm dc}. \end{align*} \]

The duty cycle is

\[\begin{align*} d=\frac{T_{\rm on}}{T}. \end{align*} \]

Thus

\[\begin{align*} \boxed{ \overline{u}_{\rm L}=dU_{\rm dc} } \end{align*} \]

> This is the basic idea of pulse-width modulation (PWM). Applications to motor drivers and power stages are continued in Block 14.

2.8 Applications for bipolar junction transistors

2.8.1 Darlington-Transistor

The Darlington circuit or the Darlington transistor (as a discrete element) is a simple construction, which makes it possible to control the output voltage $U_{\rm BE}$ with a considerably lower base current $I_\rm B$. In the simulation is the Darlington circuit compared to a simple bipolar junction transistor. Details can be found in Wikipedia under Darlington circuit.

2.8.2 Internal life of an operational amplifier

The operational amplifier as an “almost ideal” differential voltage amplifier represents a central component of electronic circuit technology from the next chapter on. In the chapter basics to amplifiers - feedback an ideal differential voltage amplifier was already used. In the simulation, the core of the differential voltage amplifier is simplified. Accordingly, there is no differential voltage at the input, but a small sinusoidal voltage. This is first applied to the base of the first bipolar junction transistor, which is a high-impedance input amplifier stage. The current $I_\rm C$ regulated by this in turn leads to a base of another bipolar junction transistor and then to the output amplifier stage. In the simulation, this setup achieves a differential gain of about $A_\rm D=10'000'000$. In real differential amplifiers, this is more in the range $A_\rm D ≈100'000$. Details can be found in Wikipedia under operational amplifier.

2.9 Applications for Field-Effect Transistors

2.9.1 NOT Gate

Just about all consumer electronics products have field-effect transistors at their core. In detail, this is based on CMOS technology (CMOS: Complementary metal-oxide-semiconductor) is used. The MOSFETs on the ground side and the MOSFETs on the power supply side behave in opposite ways, i.e. complementary. The simulation shows the simplest gate, the NOT gate. Another gate was considered in an introductory way.

2.9.2 Reverse Polarity Protection

Many chips (such as microcontrollers) can be destroyed by an incorrectly polarized power supply. Battery-powered electronics should have an active protection circuit for this. A diode is not practical for the power supply (why?). Instead, a MOSFET can be used, which does not pass negative voltages. Details are well explained on the page of Lothar Miller.

2.9.3 Level Converter

During electronics development, several integrated circuits (e.g. intelligent light sensor, microcontroller, intelligent LED) may require different voltage levels. This can lead to problems especially during data exchange if logic High has to be in a certain voltage range. This problem can be solved by a level converter. The level converter (also logic level converter, level shifter) enables the bidirectional connection of digital connections of different voltage levels, e.g. $5 ~\rm V$ to $3.3 ~\rm V$.

For the level converter, any N-channel enhancement MOSFET whose threshold voltage is below $1.8...2.0 ~\rm V$ can be used. This limit is due to the minimum logic level of $2.0 ~\rm V$ for logic high. For simplicity, “logic level enhancement mode MOSFET” is used, which is just optimized for the logic voltage of $3.3 ~\rm V$.

The way it works is well explained on Wikipedia and can be derived with simulation.

2.9.4 Voltage Doubler/Inverter

As a power supply for electronics, $5 ~\rm V$ or $3.3 ~\rm V$ is often used. In the following chapter, we will see that a bipolar power supply is often used for operational amplifier circuits. To be able to generate $-5 ~\rm V$ at low currents from a $5 ~\rm V$ supply, charge pumps are often used. One such can be seen in the simulation. In the oscilloscope (in the simulation below), the voltage $U_{\rm C1}$ is displayed at the input capacitor $C1$ and $U_{\rm C2}$ at the storage capacitor C1. This circuit can be found, for example, in IC ICL7660 (Renesas), LMC7660 (TI), TC7660 (Microchip) integrated. Details on how it works can be found in this video, for example.

Study Questions:

- In which state is the voltage $U_{\rm C1}$ equal to $1 ~\rm V$?
- In which state is the difference between the voltages $U_{\rm C2}-U_{\rm C1}$ across the two capacitors equal to $1 ~\rm V$?
- What happens if the voltage sources for $0 ~\rm V$ and $1 ~\rm V$ are reversed?
- How can this circuit be implemented with diodes instead of changeover switches?

2.9.5 Voltage Inverter in the Microcontroller

In some microcontrollers, a negative voltage is required internally (e.g. for operational amplifiers). Since this voltage is not supplied externally, the microcontroller must provide it via an internal circuit. The simulation shows a circuit that can be integrated into a microcontroller in this way. The ring oscillator generates a high-frequency clock signal, which drives an inverter stage (logical NOT gate). The charge can then be shoveled down via the two capacitors in such a way that the capacitor provides a negative voltage at the output. For more information, see Wikipedia under charge pump and “Inside the 8087's substrate bias circuit”.

2.9.6 H-Bridge

In many applications, current and voltage must be controlled independently of each other. This is the case, for example, with a motor (= ohmic-inductive load). There, the current is essentially proportional to the torque and the voltage to the speed. If voltage and current are to be output bipolar (or in the application: Torque and speed are to be controlled in both directions), a four-quadrant controller made of transistors is suitable. In modern integrated circuits, these are made of MOSFETs, directly equipped with the MOSFET driver, and several four-quadrant controllers can be found next to each other (e.g. the stepper motor driver DRV8835). Details can be found on Wikipedia under four-quadrant actuators.

2.9.7 MOSFET as Substitution for Diodes

Diodes always show a voltage drop given by the forward voltage. To circumvent this issue a MOSFET can be used.
The following example shows one way to cope with it, when two voltage sources should be combined (e.g. a rechargeable battery with U_1 and a nonrechargable buffer battery with U_2):

- The left side depicts a way to combine the two voltages with diodes. The higher voltages will be led through the diode. The diode of the lower voltage is set in reverse, since the cathode of the diode is on the higher voltage
  The disadvantages of this setup are:
    - One cannot choose the voltage on the output. It will be always given by the highest

    voltage.
    - There will always be the voltage drop of the diode
- The right side shows an alternative way to connect both voltages: the antiparallel p-MOSFETs avoid conductivity via the due to the body diode. The MOSFET pair is driven by a BJT in order to have a digital signal as an input.
  The disadvantages of this setup are:
    - It is possible to short-circuit both voltages
    - It is more complex

Often the rightside one can be simplified and the disadvantages can be avoided by using integrated circuits (like LTC4417)

2.9.8 Other MOSFET Applications

MOSFETs are not only used for pure switching of currents. Further applications are also:

1. as a display element in TFT screens (TFT ... Thin Film Transistor).
2. as memory element e.g. in SD cards Floating Gate Transistor, or also new approaches, like Ferroelectric_Random_Access_Memory)
3. as an integrated “upstream” element for power bipolar junction transistors, especially in the Bipolar_transistor_with_insulated_gate_electrode (IGBT)
4. as a chemical sensor for various materials (see Chemical_sensitive_field_effect_transistor)
5. as a link between photonics/optoelectronics and classical electronics

Exercises

Exercise 2.8.1 Current/Voltage/Power limitations

Imagine you work at the company “mechatronics and robotics” and you try to build an IoT device for vehicles.
This device shall use the power of the $12 ~\rm V$-battery of the vehicle to send regular information over Wifi. The Wifi IC needs $3.3 ~\rm V$ supply voltage and drains up to $800 ~\rm mA$ when sending signals.

To get the supply voltage a linear regulator shall be used. In detail, you want to use the LM317 regulator. A linear regulator acts as a regulated shunt resistor, which regulates its voltage drop to have a fixed output value. The output value can be regulated with a voltage divider.

1. Investigate the LM317 datasheet in order to find out, whether the LM317 is suitable for the operating conditions:
    1. input voltage $V_{\rm I,max}=14 ~\rm V$,
    2. output voltage $V_{\rm O} =3.3 ~\rm V$ and
    3. output current $I_{\rm O} =0.8 ~\rm A$.
2. When the linear regulator acts as a shunt resistor, how can the power loss $P_{\rm loss}$ be calculated?

3. With the power loss $P_{\rm loss}$ the temperature of the IC will rise. The power loss takes place within the junction. This creates a temperature drop $T_{\rm Jx}$ between the junction and surrounding. The IC will get soldered onto a PCB, and therefore the temperature drop $T_{\rm JB}$ between junction and board is most important. These temperature drop can be calculated by: $\Delta T_{\rm JB}= T_{\rm J} - T_{\rm B} =R_{\theta \rm JB}\cdot P_{\rm loss}$, where $R_{\theta \rm JB}$ is the junction-to-board thermal resistance.
    1. Search for the thermal information of the LM317 in the datasheet and calculate the maximum temperatures of the junction $T_{\rm J}$, when the temperature of the board $T_{\rm B}$ is $30 ~\rm °C$.
    2. Which package of the IC can be used, when the operating virtual junction temperature $T_\rm J$ in the recommended operating conditions shall not be exceeded?

Exercise 2.10.1 beta factor on BJT

1. A bipolar junction transistor shows with a load the collector current $I_\rm C = 398 ~\rm mA$ and the base current $I_\rm B= 2 ~\rm mA$. What is the value of the current gain β?
2. A quite common BJT is the BC847, which can be bought from multiple suppliers. Given the datasheet from BC847 - Nexperia, what is the needed base current $I_\rm B$, when a collector current of $I_\rm C=2 ~\rm mA$ shall be driven? Calculate $I_\rm B$ for all 3 groups of BC847 transistors in the datasheet.

Exercise 2.10.2 Voltage calculation

Given is the circuit shown in the simulation below.

1. For the first situation the base current is given with $I_ \rm B=50 ~\rm µA$, and the current gain $\beta=150$.
   Calculate the voltage drop $U_\rm L$ on the load $R_\rm L$ and $U_{\rm CE}$.
2. For the second situation, the base current of $I_\rm B=250 ~\rm µA$ is needed.
    1. In order to do so: calculate first $U_{\rm BE}$ of the first situation. $U_{\rm BE}$ is assumed to be constant.
    2. Calculate the correct value of R.
    3. Run the simulation and set R to the calculated value. Try to measure β. Why is it not 150 anymore?

Exercise 2.10.3 Low Side Switch and High Side Switch

Given is the circuit shown in the simulation below. The transistor is called either a “High Side Switch” or a “Low Side Switch”, depending on the voltage which is directly connected to it. In the depicted circuits each transistor drives a load resistor of $10 ~\Omega$. The input to the base/gate is a logic signal with $0 ~\rm V$ and $5 ~\rm V$ as a voltage level.

1. Explain the advantages of the MOSFET compared to the BJT based on this application.

2. Change the voltage VCC from $5 ~\rm V$ to $15 ~\rm V$, with the switch on the lower left corner. Are the transistors still able to switch in all configurations?
3. How can the problem be solved? Try to combine the BJT low-side switch as a driver with the FET high-side switch.

Exercise 2.10.4 Simple Temperature Detector

Given is the circuit shown in the simulation below. R_2 is an NTC resistor, which is used to detect the rise over a threshold temperature.

1. At first, the series resistor in front of the LED has to be calculated. For this, the voltage drop $U_{\rm CE}$ of the BJT can be neglected. The given LED lights are bright for about $10 ~\rm mA$ (lighting starts for about $1 ~\rm mA$). The supply voltage is $U_\rm S=5.0 ~\rm V$ and the forward voltage of the LED is $U_{\rm LED}=1.7 ~\rm V$.
    1. What is the ideal value of $R_ \rm D$?
    2. The value in the simulation is not correct. Which effect does this have?
2. At second, the system shall be designed for a temperature threshold of $T_0=50 ~\rm °C$.
    1. The $R(T)$-characteristic the NTC R_2 is shown in the diagram below. What is the value of $R_2(T_0)$?
    2. The BJT is conducting for $U_{\rm BC}=0.6 ~\rm V$. What is the correct value for R_1?

draw.io Start drawing by clicking here

Learning questions

for self-study

- Describe the function of a transistor.
    - Sketch the layered structure of a bipolar junction transistor. Explain the switching through of a PNP bipolar junction transistor with the help of the sketch drawn.
    - Draw the simplified diode equivalent circuit of an NPN transistor and describe the working.
- Explain the difference between a PNP and NPN transistor.
    - Draw a circuit each with the respective switch connected to $U+ = 5~\rm V$ and ground in such a way that switching through is possible with a voltage between U+ and ground at the base.
    - Name the respective connections of the transistors in the drawing.
    - What voltage must be applied to the base in each case for the transistor to switch

    through?
    - How should the sign of the control current be chosen in each case?
    - In what size range is a typical current gain?
- Current-controlled and voltage-controlled transistors
    - Explain the difference between a current-controlled transistor and a voltage-controlled transistor.
    - Which type of transistor is current-controlled and which is voltage controlled?
    - Draw a circuit diagram each for a current-controlled transistor and a voltage-controlled transistor.
    - What is the doping order of the transistors drawn?
- What are the two basic types of transistors?
- MOSFET
    - What are the advantages of a MOSFET over a bipolar junction transistor?
    - How is a MOSFET constructed? (layer structure, connections)
- H-bridge
    - Draw an H-bridge with switches (ideal switch), a resistive/inductive load, and an external voltage source with V+ and GND.
    - How can the various switches be controlled to have any voltage between V+ and V- applied to the load? What is the technical term for the method of control?
- Draw the PWM signal necessary to generate a sinusoidal output when a full bridge is used.
- What are the uses for transistors
    - What are some uses for transistors?
    - Draw a voltage doubler.
    - What is a level converter?
    - Why is it preferred to use field-effect transistors rather than bipolar junction transistors nowadays?

with answers

Looking at the picture above, which of the following statement(s) is/are correct?

- ☐ The transistor has an NPN structure internally.
- ☐ The collector terminal is at the bottom.
- ☐ It is a bipolar junction transistor.
- ☐ To make $I_\rm C$ flow, the voltage $U_{\rm BE}$ must become positive.

Which statement(s) about bipolar junction transistors is/are correct?

- ☐ The current $I_\rm C$ or the voltage $U_{\rm BC}$ controls the current flow $I_\rm B$.
- ☐ The input characteristic of a bipolar junction transistor corresponds to that of a diode.
- ☐ The disadvantage of the bipolar junction transistor is the continuous current flow required in the conductive state.
- ☐ VCC stands for Voltage Common Connector.

Which statement(s) about MOSFETs is/are correct?

- ☐ MOSFET stands for the structure of the field-effect transistor made of metal oxide and semiconductor.
- ☐ Due to the body diode, the MOSFET acts in one direction like a diode.
- ☐ Enrichment type MOSFET are conductive with $U_{\rm GS} =0 ~\rm V$.
- ☐ In N-channel MOSFETs, holes are the current-carrying charge carriers.

Check answers
You Scored % - /

Further reading

- a nice clip about the background why the MOSFET is probably the most significant invention of the 20th Century.