1 Amplifier Basics

Student Group

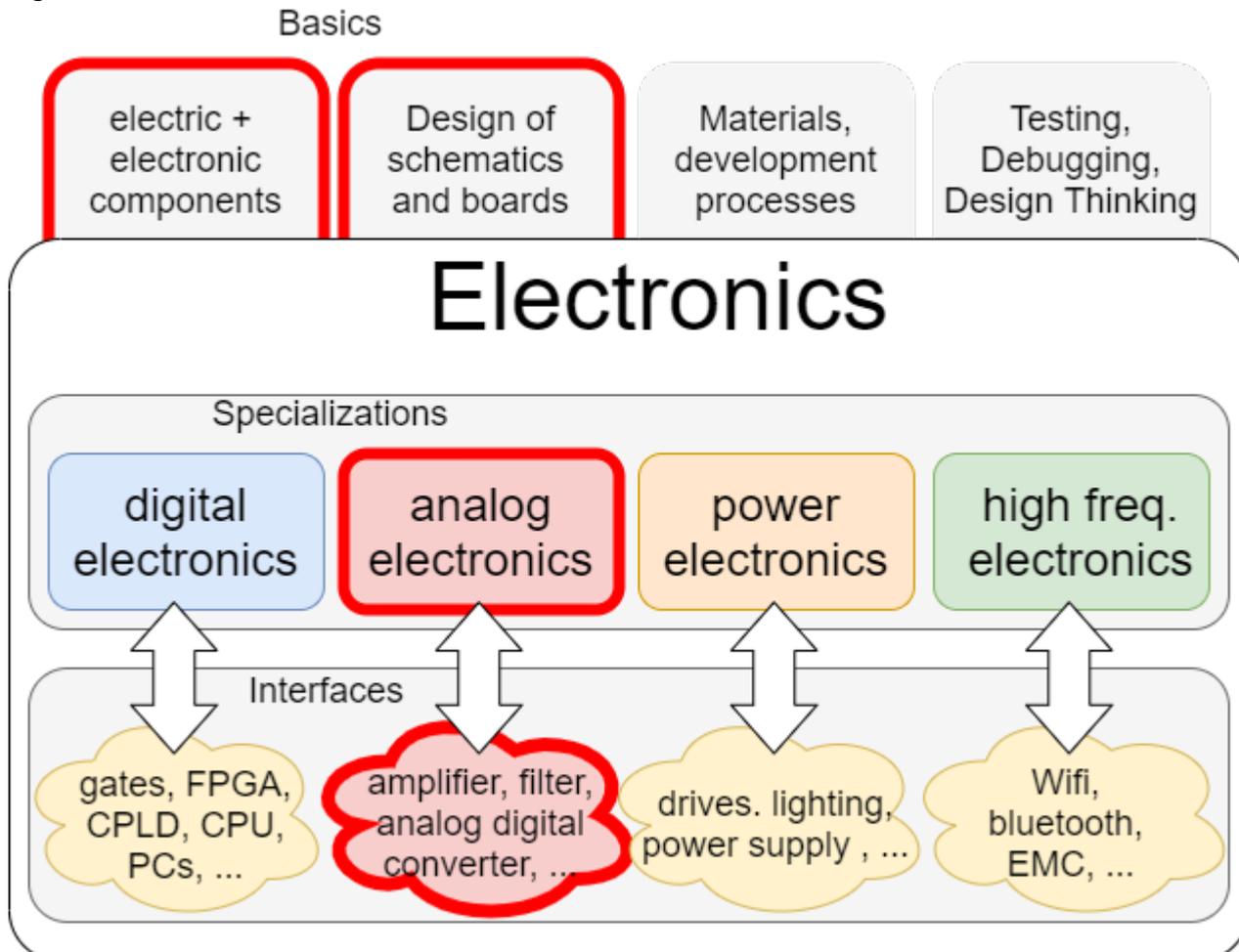| First Name	Surname	Matrikel Nr.

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1. Amplifier Basics

1.0 What is circuit design?

Fig. 1: Overview of the different areas of electronics

Circuit design encompasses various subfields of electronics. figure 1 shows the basics of electronics, its specializations and the interfaces.

In the subject Introduction to digital Systems digital technology with gates and various simple programmable circuits have already been described. In electrical Engineering 1 the foundations for simple electrical components and circuits were laid.

Circuit design now concentrates on electronic components and their circuits that affect analog electronics. Die elektronische Schaltungstechnik konzentriert sich nun auf elektronische Komponenten und deren Schaltungen, welche die Analogelektronik betrifft.

These components and circuits often connect the digital with the analog world or adjust voltages and currents for other sub-circuits. In addition, the components "transistor (TRANSfer ResISTOR)" and "diode" form the basis for both digital, power and high-frequency electronics. Without exaggerating,

these components are the basis of the modern world; today they form the heart of every computer and microcontroller.

But what is the difference between electronics and electrical engineering? And what does electronic circuit design mean?
For this purpose, it is useful to take a closer look at the individual parts of the term "electronic circuit design":
The German wording for "circuit **design**" is "Schaltungs**technik**". The word "Technik" here is derived from the Greek "τέχνη" (téchne) and means as much as art or craft. At first glance, this seems a bit surprising, since "Technik" is rarely associated with an artistic activity such as painting. In the higher semesters, however, you will learn that understanding, for example, the arrangement of electronics (circuit design) and the application of the individual components requires a trained skill and creativity. This is also true for the English "design".

A **circuit** is an arrangement of electrical or electronic components to form a functioning whole or an electric circuit. We already got to know the term circuit in electrical Engineering 1.

Electronics is derived from the word electrons. This "electron engineering" considers circuits in which an electric current or voltage is controlled by other electric signals. This means, for example, that a voltage U_{in} controls an output voltage U_{out}. Physically, the two signals do not have to be electrically connected.

First, the term electronics will be examined in more detail using various examples. First of all, a transformer will be considered. Is this an electrical or electronic component? In a transformer, the output voltage is generated by the change in the magnetic field. The magnetic field change in turn is caused by the current change on the primary side. So there is a direct transformation (a conversion) of the signals. Thus the transformer is not an electronic component. If this is still somewhat unclear, it helps to work intensively on this chapter and to compare the following examples.

The second component to be considered is the so-called contactor. A contactor is an electrically controlled switch. In this case, a coil closes a secondary, or output-side circuit if it is energized. There is no direct electrical connection here. The contactor is often not yet regarded as an electronic, but as an electromechanical component.

The last thing to be studied is the electron tube in the light of electronics and electrical engineering. An electron tube is a vacuum vessel, with several connections. Two of the connections lead internally to one electrode each, which face each other. These can be brought to a potential difference against each other and heated. This allows electrons to escape from the electrode and generate a current to the other electrode through the vacuum. A grid is placed between these two electrodes. If this is set to an opposite potential, the current flow can be stopped. Here, the grid potential can be used to change the current flow. The electron tube is already considered as an electronic component. Nowadays the electron tube has been replaced by semiconductor components.

In this course we only deal with semiconductor electronic components and basically with silicon as semiconductor.

1.1 Why amplifiers?

The amplifier is one - if not the - central component in electronics. To understand what it is used for, various examples are shown in the three short videos.

In example 1, the amplifier is briefly explained from the point of view of acoustics.

In example 2, a sensor with variable resistance is to be evaluated. This case occurs very often with passive sensors (i.e. sensors without further signal conditioning). Many of these sensors only generate a small voltage difference or a very small current. If these sensors were connected directly to a consumer or another circuit with low input resistance, the measuring voltage would break down and the measuring signal determined from it would be falsified.

Example 3 shows different amplifiers in interaction with a microcontroller. In addition to the evaluation of sensors, a signal output is necessary for many applications. If powerful motors, LEDs, antennas or loudspeakers are to be controlled, an amplifier must convert the microcontroller signal appropriately. In addition, an amplifier can take over control tasks analogously and usually with little electronic effort.

1.2 Amplifier - a black box is going to be specified

Before the amplifier is examined in more detail in the application, the interfaces and essential characteristics are to be dealt with first.

The switching symbol of the amplifier is a rectangle with an inserted triangle. The input terminals on the left side are marked $IN+$ and $IN-$. The output terminals on the right side are correspondingly labeled $OUT+$ and $OUT-$. The input voltage U_E, or U_{IN} is applied between the input terminals and the output voltage U_A, or U_{OUT} is applied between the output terminals.

The signal to be amplified comes from any source on the left-hand side. Often this can be seen as an ideal (voltage) source - i.e. with internal resistance. The amplified signal is fed to a load on the right-hand side. In the simplest case, this load is an ohmic resistor.

Note!

An amplifier is a system that uses a low power input signal to control a much higher power output signal.

The necessary energy is taken from the power supply!

Characteristics

Fig. 2: Amplifier with source and load

A voltage amplifier is required for most applications. Accordingly, this is the basis for the following explanation. However, the determined values apply also to other amplifiers. In figure 2 a voltage amplifier is shown as a black box. The voltage amplifier always tries to output a given multiple of the input voltage U_I (in German: Eingangsspannung U_E) at the output as output voltage U_O (in German: Ausgangsspannung U_A). This "multiple" can be determined as a ratio.

input circuit   Amplifier   output cicuit
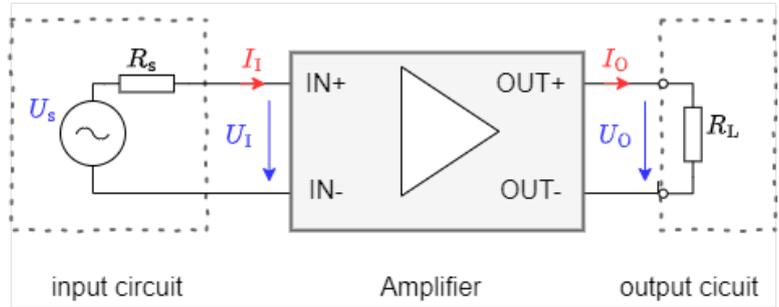
Below a simulation of an ideal amplifier is shown. The input source specifies the voltage to be amplified. The amplifier with amplification factor 100 has the connections for input and output voltage drawn in. On the right side a resistor is provided as load; this can be varied via a switch.

In the simulation some characteristics of an amplifier can be seen:

1. Ideally, no current flows into the amplifier on the input side.
2. The current on the output side depends on the connected load. If the load resistance is reduced with the help of the switch, the current increases. The amplifier thus tries to maintain the desired voltage.
3. On the output side of the amplifier, the current can flow in either direction.
   The amplifier adjusts the current so that the amplified voltage $U_A=\pm 2.5V$ can be measured at the output.

Characteristics

Characteristic groups	#	Characteristic (deutsch)	Characteristic (english)	Formula
Ratios	1	Spannungsverstärkung A_V	Voltage Amplification A_V	$\large{A_V =\frac{U_A}{U_E}}$
	2	Stromverstärkung A_C	Current Amplification A_C	$\large{A_C =\frac{I_A}{I_E}}$
	3	Übertragungswiderstand $R\_ü$	Transmission Resistance, Transimpedance R_T	$\large{R_ü =\frac{U_A}{I_E}}$
	4	Übertragungsleitwert (Steilheit) G, S	Transmission Conductance, Transconductance (Slope) S	$\large{G = S = \frac{I_A}{U_E}}$

| Characteristic groups	#	Characteristic (deutsch)	Characteristic (english)	Formula
Input/Output Resistance	5	Eingangswiderstand R_E	Input Resistance R_I	$\large{R_E =\frac{U_E}{I_E}}$
	6	Ausgangswiderstand R_A	Output Resistance R_A	$\large{R_A =-\frac{\Delta U_A}{\Delta I_A}}$
Reverse gains	7	Spannungsrückwirkung A_{rV}	Reverse Voltage Gain	$\large{A_{rV} =\frac{U_E}{U_A}}$
	8	Stromrückwirkung A_{rC}	Reverse Current Gain	$\large{A_{rC} =\frac{I_E}{I_A}}$

The ratios of the input and output quantities of a black box are called **characteristics**. A well-known parameter is, for example, the efficiency $\eta = \frac{P_A}{P_E}$. In the case of an amplifier, only the voltages and currents are considered as input and output quantities. Various amplifier parameters are shown in the table.

Different transmission ratios result, depending on the desired input variable and the output variable, which is to be controlled. It is important that the transfer resistance $R_ü$ and the transfer conductance S do not correspond to any electrical component, since current and voltage are not measured at the same terminals.

If current and voltage at the same terminals are put into relation, the input resistance $\boldsymbol{R_E}$ and the output resistance R_A result. From electrical engineering 1 it is known that for an equivalent resistance of a system the quotient of open circuit voltage U_{OC} and short circuit current I_{SC} can be used. Important: A resistor must always be considered in the passive sign convention: For a (positive) resistance value, the current and voltage arrows must be plotted in the same direction. For input resistance this is already the case (see also figure 2). However, for output resistance $\boldsymbol{R_O}$ (in the amplifier), the arrow of U_O and I_O is antiparallel. The quotient is a negative value and must be negated accordingly. However, for the output resistance, the measurement of the short-circuit current $I_{O,SC}$ is also problematic. At the beginning of this subchapter it was already described that the voltage amplifier always tries to output a given multiple of the input voltage U_I at the output as input voltage U_O. It would also attempt to do this in the event of a short circuit. The current I_O would accordingly become very large. When measuring the short-circuit current $I_{O,SC}$, the disproportionately increasing losses $P=R_O\cdot I_O^2$ via the output resistance could then destroy the amplifier. Thus, determining the output resistance via the quotient of U_O and I_O is not possible. Since the output resistance is assumed to be an ohmic resistance - i.e. slope in the U-I diagram - any two (load) points on the straight line can be used to form the quotient. Specifically, when measure the output resistance, one can measure the situation of the amplifier output with two different loads $R_{L,1}$ and $R_{L,2}$ and find the differences $\Delta U_O=U_{O,1}-U_{O,2}$ and $\Delta I_O=I_{O,1}-I_{O,2}$.

The most important characteristics of the voltage amplifier are the voltage gain A_V, as well as the input and output resistance R_I and R_O.

Equivalent circuit diagram

Fig. 4: Amplifier with source and load (with real voltage sources)

input circuit   "depending source"   output circuit
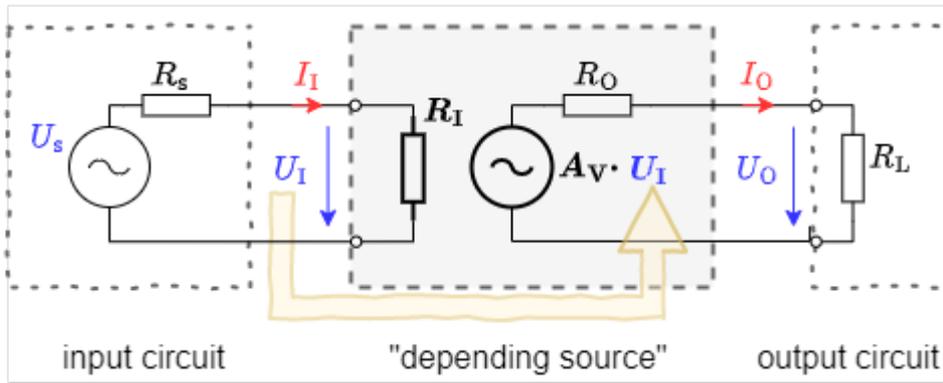
After the view on the characteristics, the first attempt will be made to understand the internal structure of the amplifier. In the previous section, current-voltage relationships were determined from the external view. There, an input resistance R_I was described on the input side of the amplifier. This is now taken into account in the equivalent circuit diagram (see figure 4). A resistance was also determined on the output side by considering it as a black box. Here, however, it must also be noted that the amplifier - according to its name - has to amplify the input signal. So here, besides the output resistor R_O, also an element has to be used, which outputs the amplified voltage. [1]. The voltage of the voltage source depends on the voltage applied to the input resistor R_I. It is more precisely larger by the factor of the voltage gain A_V.
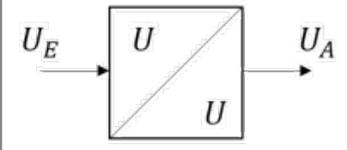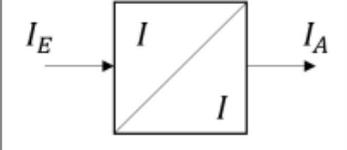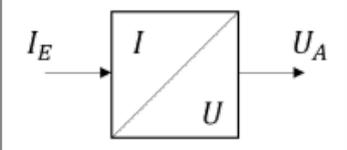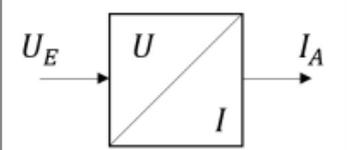
The simulation shows a **(simulated) real amplifier**. The input source has a high internal resistance. This means it has a high impedance and can only supply a small amount of current. The amplifier with a gain of 100 has - beside the connections for input and output voltage - also connections for the supply voltage drawn in. On the right side a resistor is provided as load; this can be varied via a switch.

In the simulation some properties of an amplifier can be seen:

1. On the input side, a small current flows into the amplifier.
2. The current on the output side depends on the connected load. If the load resistance is reduced with the help of the switch, the current increases. The amplifier thus tries to maintain the desired voltage.
3. The amplifier can output current as well as absorb current.
   The current on the output side flows in and out of the amplifier through the supply voltage connections.
4. The simulation is based on a real amplifier. This has a small deviation from the expected value $U_A=\pm 2.5V$ at the output voltage. Part of the deviation will be described later in this chapter.

Idealized Amplifier Base Types

Idealized Amplifier Base Types

#	Amplifier	Symbol	$\boldsymbol{R_I}$	$\boldsymbol{R_O}$	gain
1	voltage amplifier	U_E U / U U_A	$\large{\rightarrow \infty}$	$\large{\rightarrow 0}$	$\large{A_V =\frac{U_O}{U_I}}$
2	current amplifier	I_E I / I I_A	$\large{\rightarrow 0}$	$\large{\rightarrow \infty}$	$\large{A_C =\frac{I_O}{I_I}}$
3	current-to-voltage converter	I_E I / U U_A	$\large{\rightarrow 0}$	$\large{\rightarrow 0}$	$\large{R_ü =\frac{U_O}{I_I}}$
4	voltage-to-current converter	U_E U / I I_A	$\large{\rightarrow \infty}$	$\large{\rightarrow \infty}$	$\large{S =\frac{I_O}{U_I}}$

Depending on which input variable shall change which output variable, different basic amplifier types result. These are listed in the table above. As a symbol in [block diagram]s, a square with a diagonal is drawn for the respective basic amplifier type, which contains the corresponding formula symbol on the input and output side.

Now the **input resistance** $\boldsymbol{R_I}$ and **output resistance** $\boldsymbol{R_O}$ for ideal voltage amplifiers shall be considered in more detail. If a voltage is th input, the input resistance should load the source as little as possible so that the voltage to be measured does not collapse (cf. figure 4). This can also be easily checked in the simulation of the real amplifier (see above). If the resistance of the load is increased there (double-click), it approaches the input resistance of the amplifier. If the value is set to $1 M \Omega$, the voltage collapses to half. The source resistance is then equal to the input resistance of the amplifier. It is therefore important that the input resistance is as high as possible, or ideally tends towards infinity.

A similar consideration can be made for the **output resistance** $\boldsymbol{R_A}$. If a voltage is the output parameter, the output resistor must be dimensioned in such a way that the voltage at the load does not drop at the output either. The output resistance should be as small as possible so that the voltage dropping there becomes low.

Fig. 5: Amplifier with source and load (with real current sources)
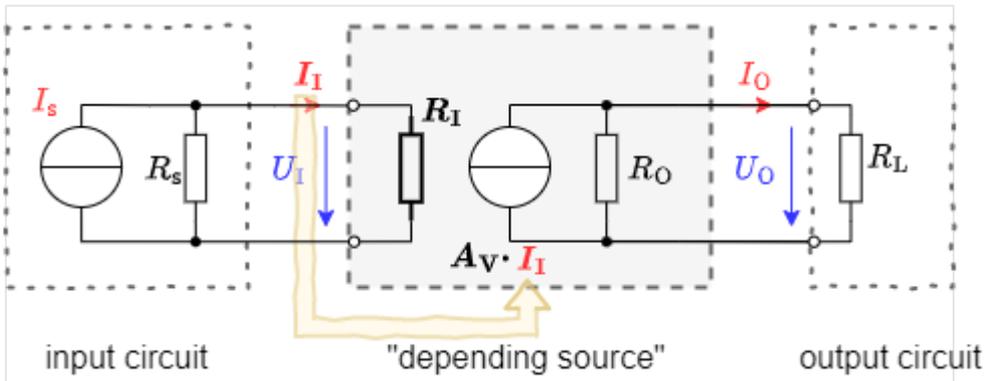
Now, if the **input resistances** $\boldsymbol{R_E}$ **and output resistances** $\boldsymbol{R_A}$ **for __ideal current amplifiers__** are considered, a different view of the amplifier is favorable. In the figure 5 the same amplifier considered so far can be seen. However, in this case all real voltage sources are replaced by real current sources. This transformation has already been described in Electrical Engineering 1. Depending on the considered electrical quantity, one or the other real source can be advantageous.

The input and output resistance of the current amplifier shall be considered with this knowledge. On the input side, most of the input current I_I should flow into the amplifier. The input resistance R_I must accordingly tend towards zero. The maximum current should also flow out of the amplifier at the amplifier output. Here, the output resistance R_O must accordingly tend towards infinity, so that the lowest possible current flows through it.

The following applies to **current-voltage and voltage-current converters**:

1. The respective name is composed of input variable-output variable.
2. For the input and output resistances, the respective corresponding consideration of the ideal current amplifier or voltage amplifier can be used.

1.3 Feedback

Fig. 6: Block diagram of a amplifier with feedback
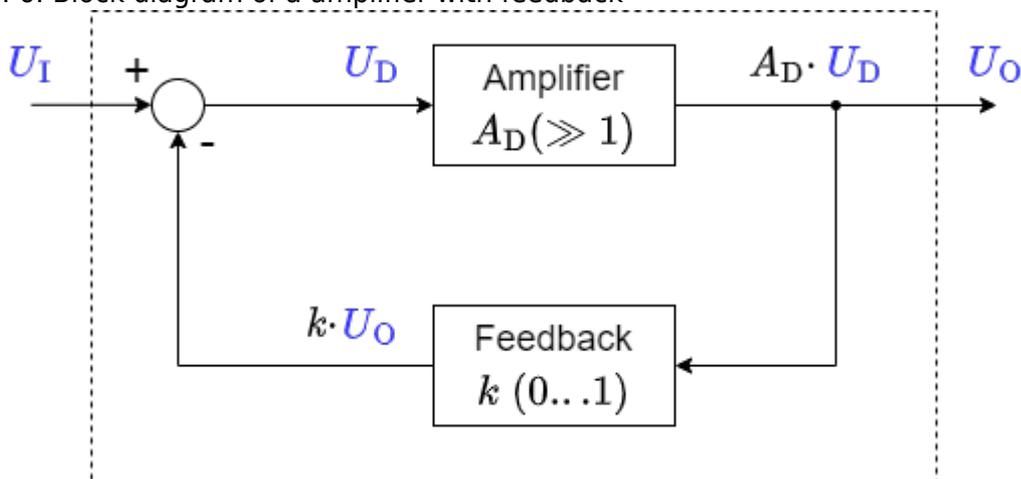
One of the fundamental principles of control engineering, digital technology and electronics is **feedback**. Thus, in the introduction to digital systems, the output value of a NOR gate was already fed back to its input via detours for in order to create a flip-flop. Similarly, here the output value of the

ideal amplifier is to be fed back to the input. In contrast to digital systems, in control engineering and electronics a fraction (in rare cases: a multiple) of the output value is fed back.

In addition, there is another tool for control engineering, digital systems and electronics: the **block diagram** or signal flow diagram. In Electrical Engineering 1, circuit diagrams have been used so far. With circuit diagrams there is an interaction of all components due to Kirchhoff's rules, furthermore voltage differences everywhere or current can be measured over all components.

In contrast to this is the block diagram. This shows individual blocks which link a cause with an effect. In general, no reaction of the effect on the cause is assumed. Causes and effects can be voltages or currents, which are then written on the respective connecting arrow. The block diagram does not claim to conserve energy or charge, but serves to provide an overview of the effects and interrelationships. Thus Kirchhoff's rules are usually not applicable there.

figure 6 shows a block diagram of a feedback amplifier consisting of an ideal voltage amplifier with gain A_D drawn in the center. The output voltage U_O, reduced by the factor k, is fed back via a feedback element. The circle symbol with the arithmetic symbols (in the block diagram on the left) shows how the incoming values must be offset against each other. The value $k \cdot U_O$ is thus subtracted from the input value U_I in the indicated block diagram.

The advantage of a real amplifier in negative feedback is that the gain A_V of the whole system depends only negligibly on the gain factor A_D of the real amplifier, if A_D is very large (see also task 1.3.2). In this case, the gain $A_V=\frac{1}{k}$. To avoid oscillation of the whole system, the amplifier must contain a delay element. This is present in the real amplifier in such a way that the output voltage U_O cannot change infinitely fast. [2] (see also task 1.3.1).

Note: feedback, positive feedback, negative feedback

Feedback (German: **Rückkopplung**) refers to the return of part of the output signal of an amplifier.
With **positive** (German: **Mitkopplung**) feedback, the part of the output signal with positive sign is fed back. The output value is therefore always increased by the input value.

With **negative feedback** (German: **Gegenkopplung**), the part of the output signal with a negative sign is fed back.
The output value therefore always attenuates the input value.

Note: Gain factors

The **differential gain** or **open-loop gain** $\boldsymbol{A_D}$ (German: Differenzverstärkung) refers only to input and output voltage of the inner amplifier: $A_D=\frac{U_O}{U_D}$. This acts only without external feedback. It is also called open-loop gain.

The **voltage gain** $\boldsymbol{A_V}$ refers to input and output voltage of the whole circuit with feedback: $A_V=\frac{U_O}{U_I}$. It is also called closed-loop gain.

[1] The voltage source used in the amplifier is a dependent source, this term will not be discussed further in this course.
[2] That a voltage change can only take place in finitely long time is also true for the input

voltage. However, this cannot be influenced by the amplifier, but is externally specified. 2

Exercises

Learning questions

for your self-study

- What is the definition of an amplifier?
- Explain with an example what is the essence of an amplifier.
- How do you determine the input and output resistance of an amplifier?
- How should the input and output resistance be selected for a current amplifier? Why?
- When is it called positive feedback and when is it called negative feedback?
- Explain the principle of negative feedback.
- What is the difference between voltage gain and differential gain? Briefly describe the difference between A_V and A_D.
- How does A_D affect the output voltage U_O when there is no feedback in an op-amp circuit?
- What is the effect of A_D on the output voltage U_O when feedback is present in an op-amp circuit and A_D is increased from 100,000 to 200,000?
- At what value for k does the feedback become maximum?
- What values can k take for a passively feedback amplifier?
- What effect does k have on the amplifier?
- What happens if you feed back the entire output voltage?

with answers

How is the output resistance of an amplifier defined?

- ☐ $R_O = \Delta U_I / \Delta I_O$
- ☐ $R_O = U_I / I_O$
- ☐ $R_O = \Delta U_O / \Delta I_O$
- ☐ $R_O = -\Delta U_O / \Delta I_O$
- ☐ $R_O = U_O / I_O$

Ideal resistances of a voltage-current converter

- ☐ $R_I \to 0$, $R_O \to \infty$
- ☐ $R_I \to 0$, $R_O \to 0$
- ☐ $R_I \to \infty$, $R_O \to 0$
- ☐ $R_I \to \infty$, $R_O \to \infty$

What can you use a linear regulator for?

- ☐ To regulate linear motors

- ☐ To output fixed voltage values
- ☐ To regulate linear circuits
- ☐ To output fixed current values

What type of amplifier produces an output current I_O from an input voltage U_I, such that an output voltage $U_O = C \cdot U_I$ with constant C is produced?

- ☐ Current-to-voltage converter
- ☐ Current amplifier
- ☐ Voltage-to-current converter
- ☐ Voltage amplifier

The transfer resistance ...

- ☐ Cannot be measured using a resistance meter
- ☐ Can be used for voltage dividers
- ☐ Is given by ${U_E} \over {I_A}$, with input voltage U_I and output current I_O
- ☐ represents the gain

check answers
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