

# 4 Basic Circuits II

## Student Group

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## Table of Contents

<b>4. Basic Circuits II</b> .....	2
Introductory Example .....	2
Objectives for Basic Circuits II .....	2
<b>4.1 Inverting Summing Amplifier</b> .....	3
Exercise 4.1.1 Transfer exercise - signals and systems .....	4
<b>4.2 Differential Amplifier / Subtractor</b> .....	4
<b>4.3 Instrumentation Amplifier</b> .....	6
Exercise 4.3.1 Instrumentation amplifier .....	8
<b>4.4 Current-Voltage-Converter</b> .....	9
<b>4.5 Voltage-to-Current Converter</b> .....	10
<b>Applications</b> .....	11
<b>Programmable Gain Amplifier</b> .....	11
<b>Exercises</b> .....	12
Exercise 4.2.1 Determination of the transmission behavior of the differential amplifier .....	13
Exercise 4.4.1 Transmission resistance of the current-voltage converter .....	14
Exercise 4.5.1 Transfer Conductance of the voltage-current converter .....	15
Exercise 4.5.2 Earth-related load .....	16
<b>Further Reading</b> .....	16
<b>Learning Questions</b> .....	16

## 4. Basic Circuits II

- Also recommended for basic circuits II is the <https://www.ablic.com/en/semicon/products/analog/opamp/intro/>
- [Operational Amplifiers \(Johan Huijsing\)](#) [viewable via the university network]

### Introductory Example

In various applications, currents must be measured. In an electric motor, for example, the torque is caused by the current flowing through the motor. A motor control and a simple overcurrent shutdown are based on the knowledge of the current. For further processing, a voltage must be generated from the current. The simplest current-to-voltage converter is the ohmic resistor. A sufficiently large voltage as required by a microcontroller, for example, cannot be achieved with this. So not only does the current have to be converted, but also the generated potential difference has to be amplified.

One such current sense amplifier is the [INA 240](#) device. This is installed as shown below. In the simulation, a real current source feeds the electrotechnical image of a DC motor on the left (in the example: inductance with  $L_{\text{L}}=10\text{~}\mu\text{mH}$  and internal resistance  $R_{\text{L}}=1\text{~}\Omega$ ). The current flowing from the motor is conducted through a measuring resistor ( $R_{\text{M}}=0.01\text{~}\Omega$ ) which is noticeably smaller than the internal resistance of the motor. Thus, most of the power acts in the motor and the current is only marginally affected by the sense resistor. The simulation above shows the inner workings of the current measuring amplifier.

The following explains ways in which such circuits can be understood.

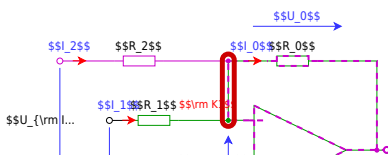
### Objectives for Basic Circuits II

After this lesson, you should:

1. Be able to apply the superposition method to operational amplifier circuits.
2. Know how differential amplifiers and instrumentation amplifiers differ (circuit, applications, advantages, and disadvantages).
3. Know what the circuit and transfer function of a voltage-to-current converter and current-to-voltage converter look like.
4. Be able to name applications for the summing inverter, voltage-to-current converter, and current-to-voltage converter.

# 4.1 Inverting Summing Amplifier

Fig. 1: Inverting Summing Amplifier



From the [inverting amplifier](#) another circuit can be derived, which can be seen in [figure 1](#). Here, both the green part of the circuit and the purple part correspond to an inverting amplifier.

How can  $U_{\text{O}}$  be calculated in this circuit? To do this, it is first important to understand what is being sought (compare [steps to the goal](#)). The goal is to find the relationship between output and input signals:  $U_{\text{O}}(U_{\text{I1}}, U_{\text{I2}})$ . Different ways to get there were explained in [Electrical engineering 1: Network analysis](#). Here we will outline a different way.

In the case of a circuit with several sources, superposition is a suitable method, in particular the superposition of the effect of all sources in the circuit. For superposition, it must be ensured that the system behaves linearly. The circuit consists of ohmic resistors and the operational amplifier. These two components give twice the output value when the input value is doubled - they behave linearly. For superposition, the effect of the two visible voltage sources  $U_{\text{I1}}$  and  $U_{\text{I2}}$  must be analyzed in the present circuit.

In **case 1** the voltage source  $U_{\text{I1}}$  must be considered - the voltage source  $U_{\text{I2}}$  must be short-circuited for this purpose. The equivalent circuit formed corresponds to an inverting amplifier across  $R_2$  and  $R_0$ . However, there is an additional resistor  $R_1$  between the inputs of the operational amplifier. What is the influence of this resistor? The differential voltage  $U_{\text{D}}$  between the inputs of the operational amplifier approaches 0. Thus, the following also applies to the current through  $R_1$ :  $I_{1(1)} \rightarrow 0$ . Thus the circuit in case 1 is exactly an inverting amplifier. For case 1,  $A_{V(1)} = \frac{U_{\text{O(1)}}}{U_{\text{I1}}} = -\frac{R_0}{R_1}$  and thus:  $U_{\text{O(1)}} = -\frac{R_0}{R_1} \cdot U_{\text{I1}}$ .

Using the same procedure, **case 2** for considering the voltage source  $U_2$  gives:  $U_{\text{O(2)}} = -\frac{R_0}{R_2} \cdot U_{\text{I2}}$ .

In superposition, the effect results from the **addition of partial effects**:

$$\boxed{U_{\text{O}} = \sum_i U_{\text{O}(i)} = - \left( \frac{R_0}{R_2} \cdot U_{\text{I2}} + \frac{R_0}{R_1} \cdot U_{\text{I1}} \right)}$$

Also, considering the node set for  $\text{K1}$  in [figure 1](#) gives the same result.

The **Inverting Summing Amplifier** (also called: Summing Amplifier or Voltage Adder) can be extended to any number of inputs. The simulation above shows the superposition of several inputs. Depending on the resistances at the different inputs, a different current flows into the circuit.

This circuit was used in analog [audio mixers](#). This allows a combination of several signals with different gains (by the input resistors  $R_i$  with  $i=1, \dots, n$ ). Furthermore, the overall gain can be changed by  $R_0$ . A big advantage of this circuit is also that the summation at node  $\text{K1}$  is done on potential  $U_{\text{D}}$ . This means that capacitive interference concerning the ground potential (and therefore the case) is virtually non-existent.

A very similar concept allows the construction of a [Digital-Analog Converter, DAC](#).

### Exercise 4.1.1 Transfer exercise - signals and systems

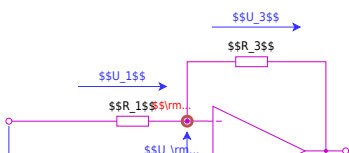
1. Which mathematical function seems to be visible from the superposition of sinusoidal signals, when these sinusoidal signals double the frequency and halve the amplitude? (This is the output of the simulation above..)
2. Which mathematical function seems to be visible in the simulation, when the voltage sources with  $80 \text{ ~}\mu\text{m Hz}$  and  $160 \text{ ~}\mu\text{m Hz}$  are removed?

## 4.2 Differential Amplifier / Subtractor

In addition to the (reverse) adder, there is also a circuit for subtracting two input values. This circuit became the core of the introductory example. But also in the simulation below this circuit is shown in another example: In this case, a [differential input signal](#) is shown on the left. Differential means that the signal on one line is not transmitted concerning a reference voltage (usually ground potential) on a second line. Instead, the signal is transmitted to both lines in opposite directions. If a disturbance acts equally on both lines (which is often the case when lines are close to each other), the effect of the disturbance can be eliminated by forming the difference.

How can the relationship  $U_{\text{O}}(U_{\text{I1}}, U_{\text{I2}})$  between output and input signals be determined for this circuit?

Fig. 2: Differential Amplifier



Again, various network analysis concepts could be used to look at the circuit (e.g. superposition or mesh and node sets). Again, another possibility is to split the circuit as color-coded in the [figure 2](#). The green part shows a voltage divider  $R_2 + R_4$ . Since the input resistance of the operational amplifier is very large, this voltage divider is unloaded. The voltage at node  $\text{K2}$  or at the noninverting input  $U_{\text{p}}$  is just given by the voltage divider:  $U_{\text{p}} = U_{\text{I2}} \cdot \frac{R_4}{R_2 + R_4}$ .

The violet part corresponds to an inverting amplifier, but the voltage at the node  $\text{K1}$  or at the inverting input  $U_{\text{m}}$  is just equal to  $U_{\text{p}}$  due to the feedback, since  $U_{\text{D}} \rightarrow \infty$ . Thus, the current flowing into node  $\text{K1}$  via  $R_1$  results from  $I_1 = \frac{U_{\text{I1}} - U_{\text{p}}}{R_1}$ . The output voltage is given by  $U_{\text{O}} = U_{\text{p}} - U_3$ , where the voltage  $U_3$  is given by the resistance  $R_3$  and the current through  $R_3$ . The current through  $R_3$  is just the same as the current through  $R_1$ , i.e.  $I_1$ .

The result is:

$$U_{\text{O}} = U_{\text{I2}} \cdot \frac{R_4}{R_2 + R_4} - R_3 \cdot \frac{U_{\text{I1}} - U_{\text{p}}}{R_1}$$

$$U_{\text{O}} = U_{\text{I2}} \cdot \frac{R_4}{R_2 + R_4} - U_{\text{I1}} \cdot \frac{R_3}{R_1} + U_{\text{I2}} \cdot \left( \frac{R_3}{R_1} \cdot \frac{R_4}{R_2 + R_4} \right)$$

$$\boxed{U_{\text{O}} = U_{\text{I2}} \cdot \frac{R_4}{R_2 + R_4} \cdot \frac{R_1 + R_3}{R_1} - U_{\text{I1}} \cdot \frac{R_3}{R_1}}$$

Fig. 3: Differential Amplifier - Animation

Please click to see the animation!

Two simplifications should be considered here:

1. If  $R_1 = R_2$  and  $R_3 = R_4$  are chosen, the equation further simplifies to:

$$\boxed{U_{\text{O}} = U_{\text{I2}} \cdot \frac{R_3}{R_1} - U_{\text{I1}} \cdot \frac{R_3}{R_1} = \frac{R_3}{R_1} \cdot (U_{\text{I2}} - U_{\text{I1}})}$$

This variant can be found in various measurement circuits.

2. Alternatively, if  $R_1 = R_3$  and  $R_2 = R_4$  is chosen, the result is:

$$\boxed{U_{\text{O}} = U_{\text{I2}} - U_{\text{I1}}}$$

This would also result in case 1. if  $R_1 = R_2 = R_3 = R_4$  is chosen.

The animation shows how the 2nd case would result in similar triangles. The connection of the two "seesaws" at the point  $K_1 K_2$  is caused by the operational amplifier, through which the voltage  $U_{\text{p}}$  and  $U_{\text{m}}$  converge to  $U_{\text{D}} \rightarrow 0$ .

A big advantage of this circuit is that even very large voltages can be used as input voltage, if  $R_1 \gg R_3$  and  $R_2 \gg R_4$  are chosen. This would divide the input voltages down and display a fraction of the difference as the result. The main drawback of the circuit is that the gain/attenuation depends on more than one resistor. This makes a quick choice of gain difficult.

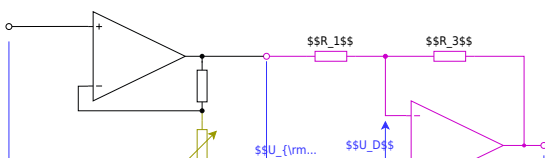
## 4.3 Instrumentation Amplifier

This type of amplifier shall be analyzed in the following exercise.

An example of a pure instrumentation amplifier is the components [ina818.pdf](#).

Often instrumentation amplifiers are used in programmable gain amplifiers (PGA). PGAs allow the manipulation of the amplification factor by a digital interface.

Fig. 3: Instrumentation Amplifier





### Exercise 4.3.1 Instrumentation amplifier

Find out how the instrumentation amplifier works through internet research.

1. Consider the illustrated Falstad Simulation below. What happens when you change the value of the variable resistance?  
Analyze especially the minimum and maximum value of the output voltage.  
In order to do so, you can start/stop the simulation with the Run/STOP button and read the output voltage by moving the mouse pointer over the output signal in the voltage-time diagram.
2. What happens if you remove the variable resistance and leave the connections open?  
Which circuit has the OPVs at the entrance?

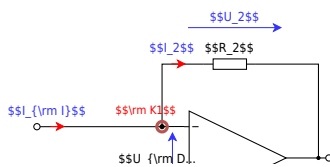
3. Compare the following situations. What is to be determined?
  1. Variable resistance is replaced by resistance with  $2 \text{ k}\Omega$ .
  2. Variable resistance is replaced at the top connection by  $1 \text{ k}\Omega$  to mass and lower connection by  $1 \text{ k}\Omega$  to mass.
  3. Variable resistance is replaced at the top connection by  $1 \text{ k}\Omega$  to a voltage source with  $1 \text{ V}$  and the lower connection also by another  $1 \text{ k}\Omega$  to  $1 \text{ V}$ .

4. Which transfer equation  $U_{\text{A}} = F(U_2, U_1, R_{\text{G}}, R)$  does the initial circuit have, when all resistances (except the variable resistance  $R_{\text{G}}$ ) have the same value  $R$ ?

5. What are the advantages of the instrumentation amplifier to the differential amplifier?

## 4.4 Current-Voltage-Converter

Fig. 5: Current-Voltage-Converter



In [figure 5](#) one can see the circuit of a current-voltage converter. The current-to-voltage converter changes its output voltage based on an input current. This circuit is also called a [transimpedance amplifier](#) because here the transfer resistance - that is, the trans-impedance - represents the gain. Generally, the gain was expressed as  $A = \frac{\text{output}}{\text{input}}$ .

In the case of the current-to-voltage converter, the gain is defined as:

$$R = \frac{U_{\text{out}}}{I_{\text{in}}} = \frac{U_{\text{out}}}{I_{\text{in}}} = -R_1$$

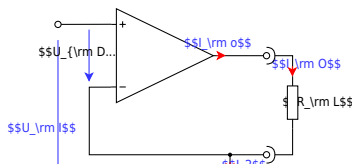
$R_1$  is the resistor used in the circuit.

In the simulation, the slider on the right (“Current of current source”) can be varied. This changes the input current and thus the output voltage.

This circuit can be used, for example, to read a [photodiode in volt-free circuit](#) ([further explanation](#) and [integrated circuit tsl250r.pdf](#)).

## 4.5 Voltage-to-Current Converter

Fig. 6: Voltage-to-Current Converter



Next, consider the voltage-to-current converter. With this, an output current is set proportional to an input voltage.

Here, the general gain  $A = \frac{\text{output}}{\text{input}}$  to

$$S = \frac{I_{\text{out}}}{U_{\text{in}}} = \frac{I_{\text{o}}}{U_{\text{I}}}$$

The quantity  $S$  is called the transfer conductance.

This circuit can be used, for example, to generate a voltage-regulated current source.

In practical applications, often specialized amplifiers, called [Operational Transconductance Amplifier](#) (transconductance from transmission conductance), are used.

## Applications

### Programmable Gain Amplifier

Often in applications an analog signal is too small to process (e.g. to digitalize it afterward).

To amplify it an OpAmp can be used. However, for a wide input range, it might be beneficial to have an adjustable scale.

This can be done with a simple non-inverting amplifier combined with a resistor network as seen in the next simulation.



**Exercise 4.2.1 Determination of the transmission behavior of the differential amplifier**

In the following, the transfer function of the differential amplifier is to be calculated. To do this, you should follow a few steps.

1. Derive the function  $U_{\text{O}} = f(U_{\text{I1}}, U_{\text{I2}})$  using superposition.
  1. To do this, first draw an equivalent circuit in each case.
  2. Briefly describe the resulting circuit. Which amplification circuit results in each case?
  3. Then calculate the voltages  $U_{\text{O1}}$  and  $U_{\text{O2}}$ , and from them  $U_{\text{O}}$ .
2. Determine the function  $U_{\text{O}} = f(U_{\text{I1}}, U_{\text{I2}})$  or the resistance values of the circuit shown.

### Exercise 4.4.1 Transmission resistance of the current-voltage converter

Derive the gain for the current-voltage converter, i.e. the transmission resistance. Use the procedure that we used for the other amplifiers.

1. Draw a circuit with the relevant voltages, currents, resistances, and the operational amplifier
2. What are you looking for?
3. What is the number of variables
4. What is the number of equations required?
5. Establishing the known equations.
6. Derivation of the transmission resistance.

**Exercise 4.5.1 Transfer Conductance of the voltage-current converter**

Derive the “amplification” for the voltage-to-current converter, i.e. the transfer conductance. Use the same procedure that we used for the other amplifiers.

1. Draw a circuit with the relevant voltages, currents, resistances, and the operational amplifier.
2. What are you looking for?
3. What is the number of variables?
4. What is the number of necessary equations?
5. Establishing the known equations.
6. Derivation of the transfer conductance.

### Exercise 4.5.2 Earth-related load



If the voltage-current converter is used as a current source, it must be ensured that the load has no contact with the ground.

1. Draw the voltage-to-current transformer with a load that is in contact with the ground.
2. Why is in this case the slope derived above no longer valid as an amplification factor?
3. Will the output current be higher or lower in this case?

## Further Reading

- [Low Dropout Controller](#)

## Learning Questions

- State applications for the reverse adder.
- Explain the working of a current-to-voltage converter.
- Name 3 applications for an operational amplifier.

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Last update: **2023/09/13 09:27**

