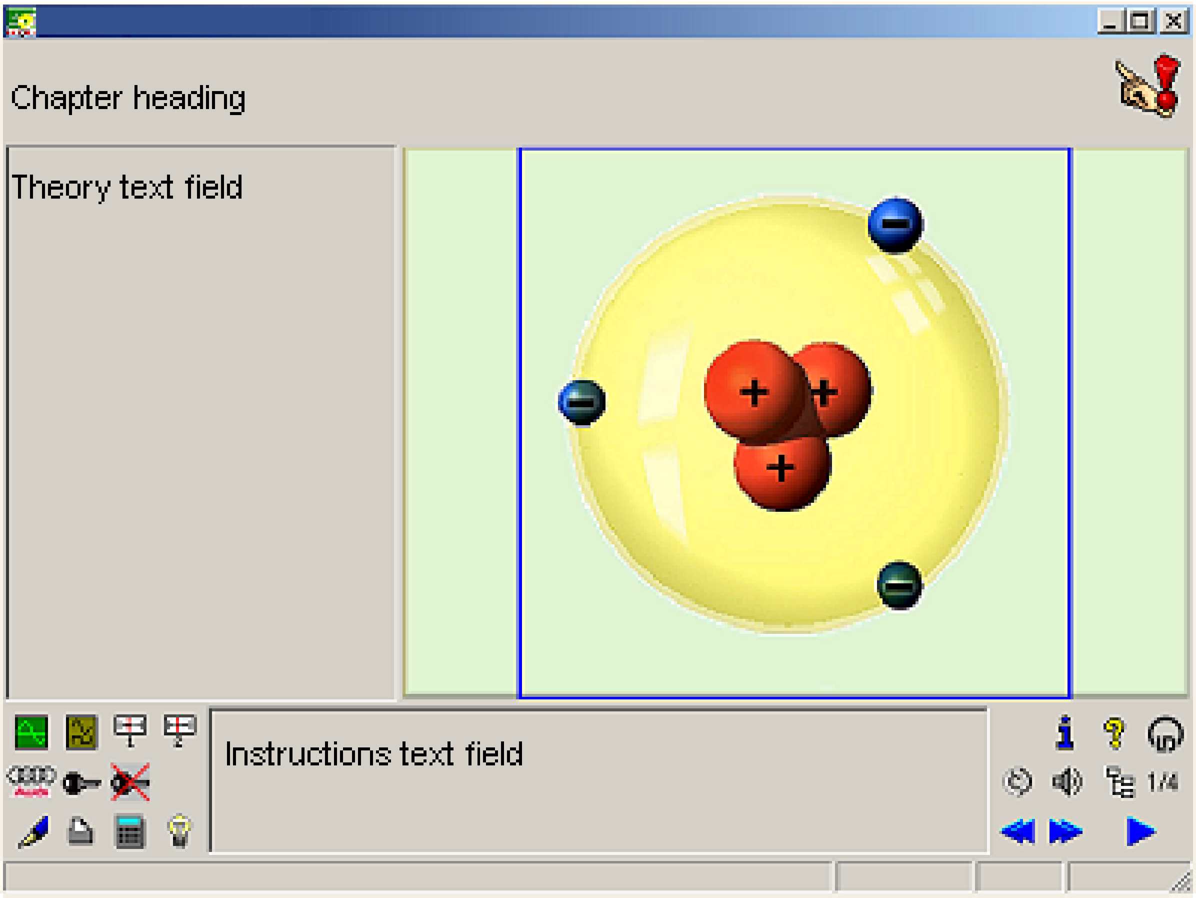
1.1 Using the course



Welcome to the COM3LAB course. Before you begin with the course, you should spend some time on the next pages with the COM3LAB System.

More detailed information can be obtained by clicking in the individual areas in the adjacent image.

1.2 Operational amplifiers

Welcome to the COM3LAB multimedia course **Operational amplifiers I**. This course is intended to give you an insight into the world of operational amplifiers. In conjunction with the experiment board, you will be taught the basic principles of an operational amplifier: Starting with standard circuits of an operational amplifier, you will realize a function generator at the end.

1.3 Introduction

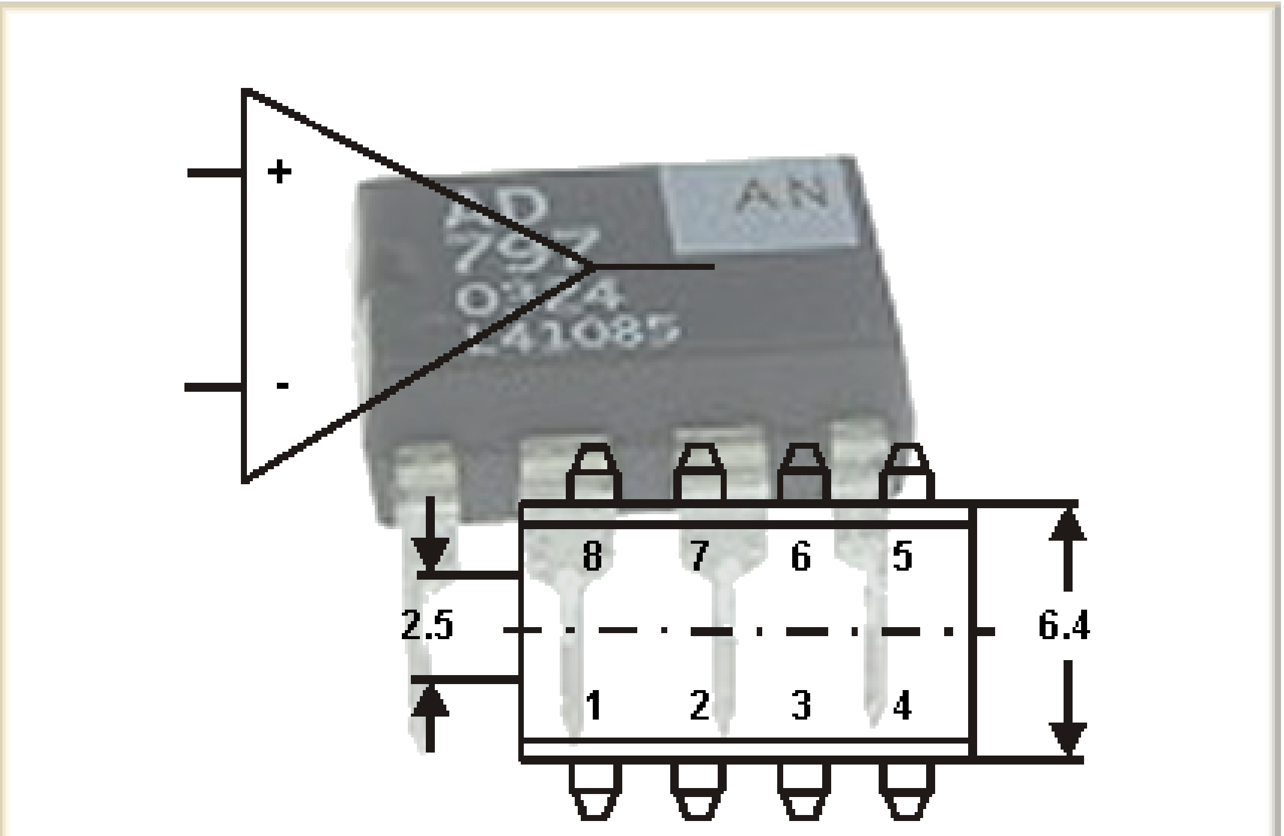
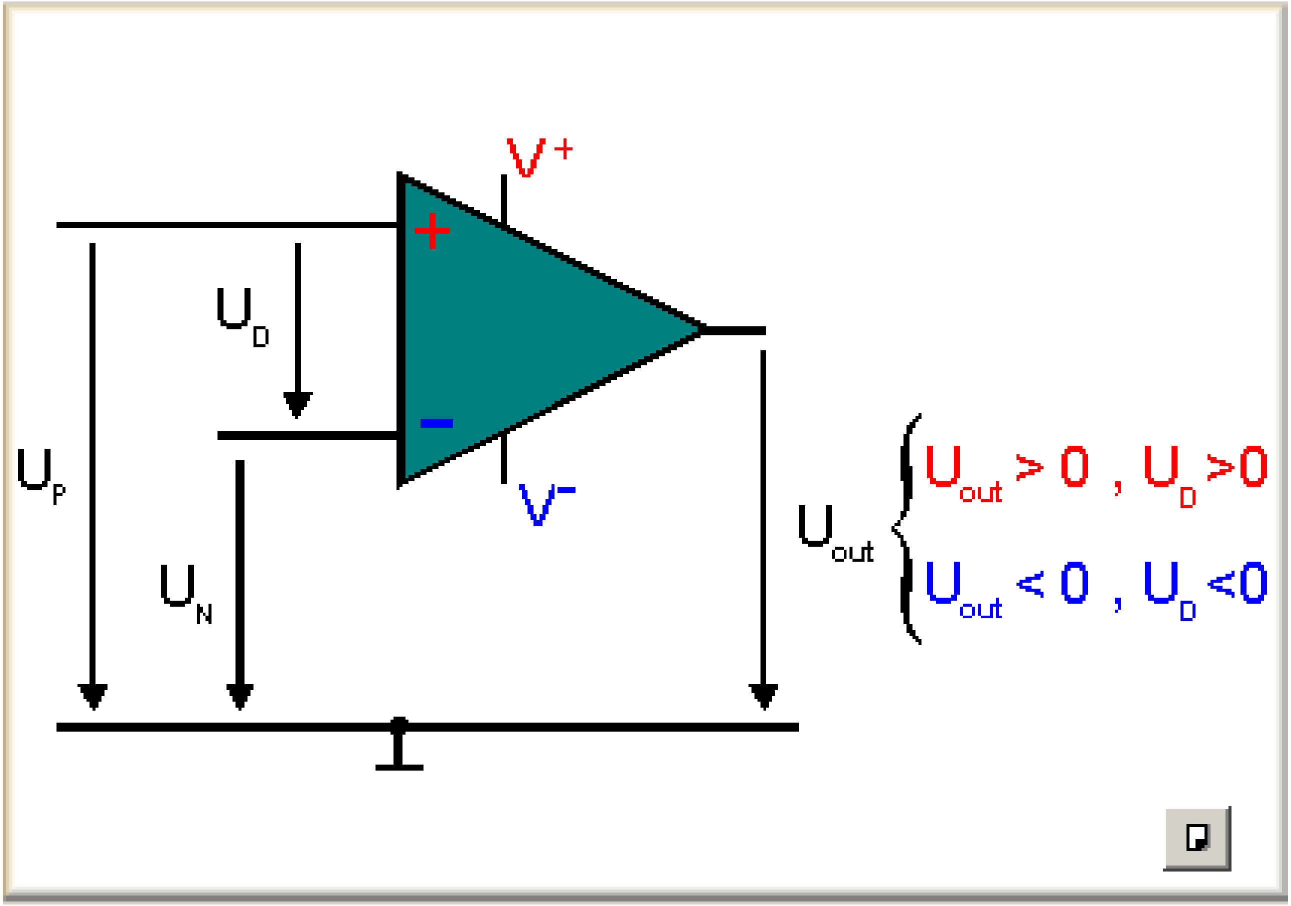


Diagram of an operational amplifier

Basically there is no difference between a usual amplifier and an operational amplifier. However, whereas the characteristics of a usual amplifier are determined by its internal design, the action of an operational amplifier can be determined by external circuit elements. An operational amplifier has a voltage gain, a high input resistance and a low output resistance. This type of amplifier used to be employed exclusively in analog computers for performing mathematical operations such as addition and multiplication. This is where the name operational amplifier comes from.

In the diagram of the operational amplifier only its outputs and inputs are drawn. In addition you see the complete diagram of an LM741 and its designs in the opposite picture. For further information click the contact pins.

1.4 Function



The operational amplifier has a difference amplifier[1] in its input. If the potential of the inverting input is higher, the output voltage is negative. If the potential of the non- inverting input is higher, the output voltage is positive. The magnitude of the output voltage depends on the difference between the input voltages and on the gain. Because of the high open-loop gain[2] the output is completely saturated even if the differences are small.

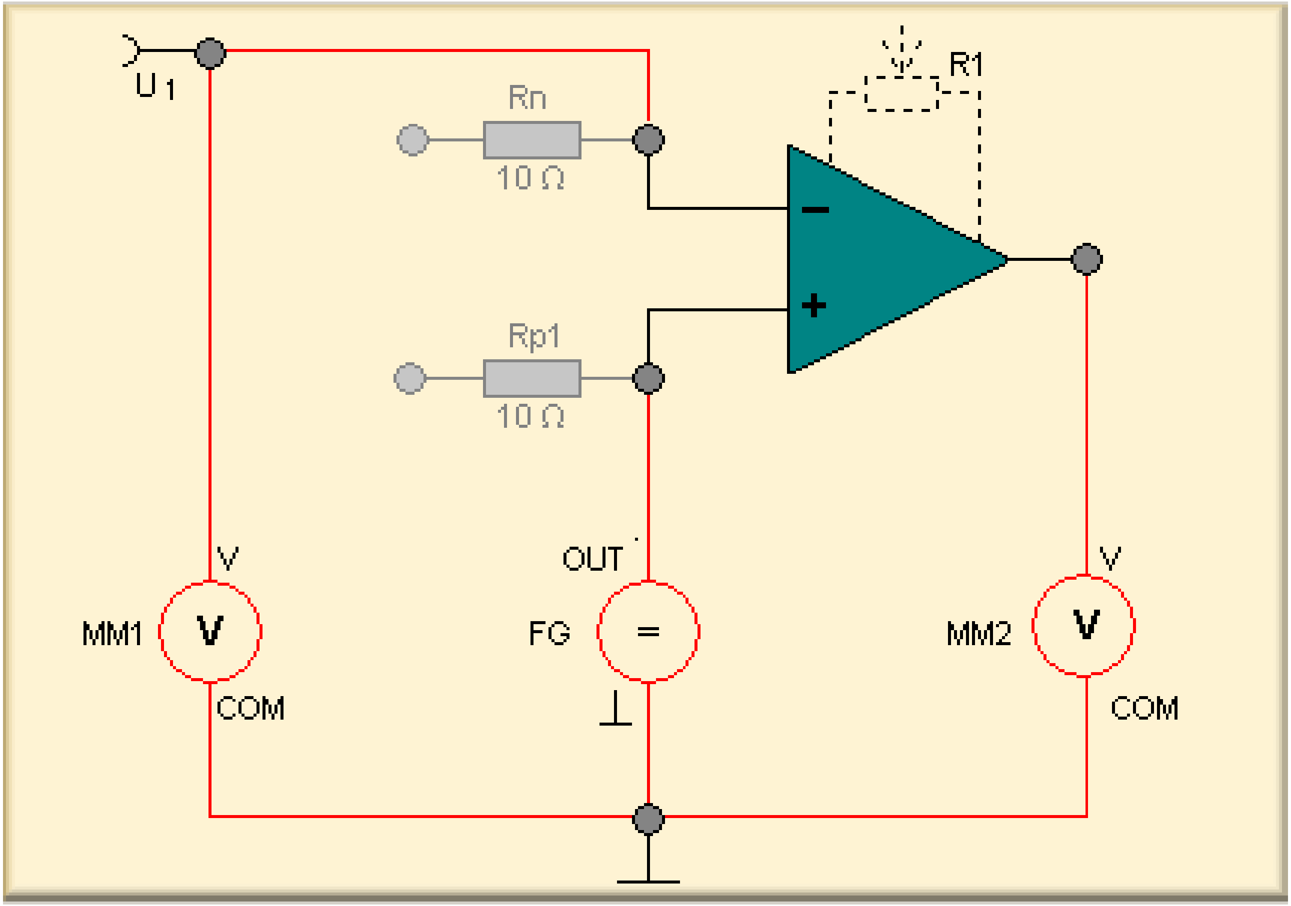
[1] **Difference Amplifier**

A difference amplifier compares the potentials at its input terminals.

[2] **Open-loop Gain**

The maximum voltage gain that in theory can be achieved with an operational amplifier is given by the open-loop gain.

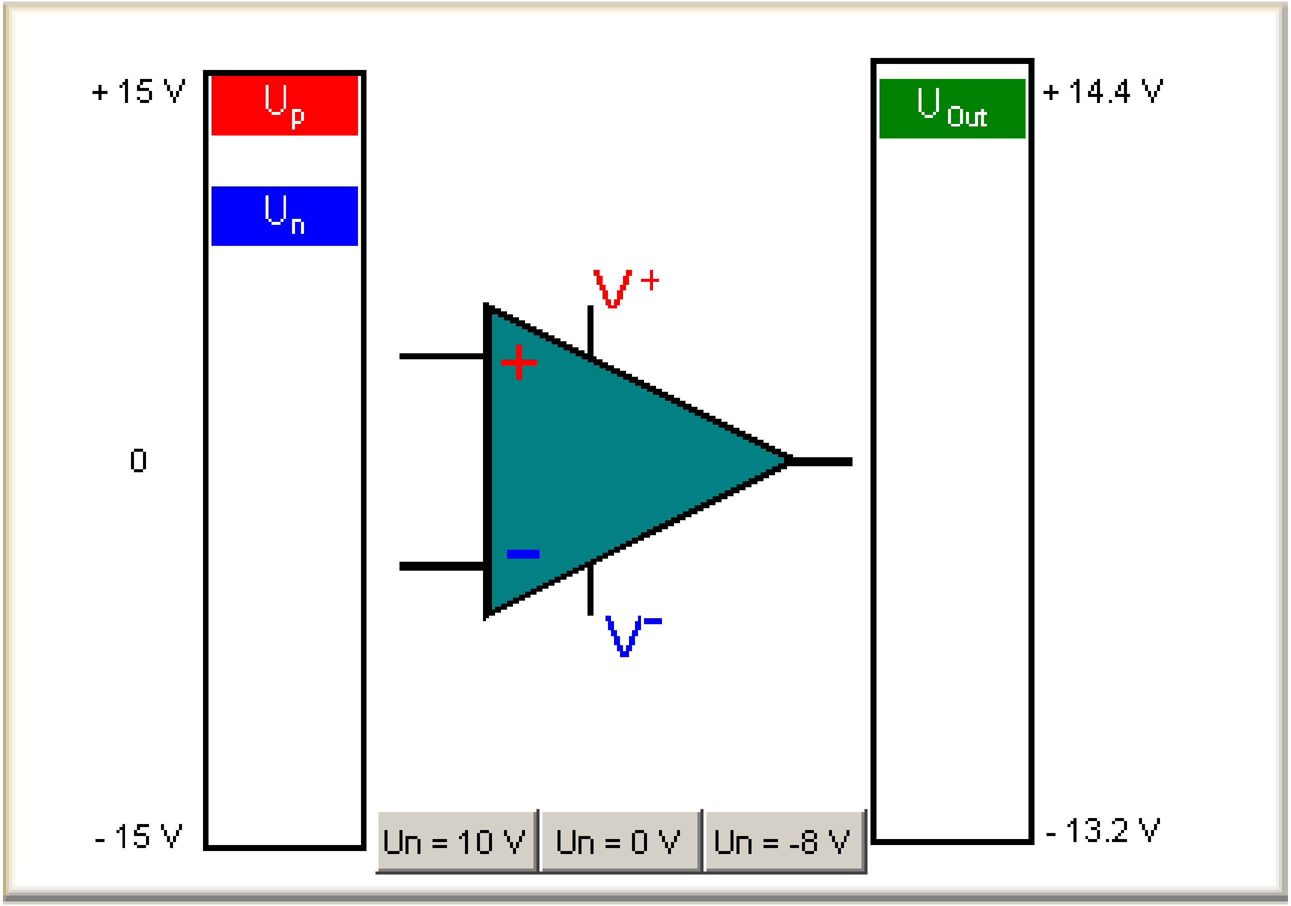
1.5 Experiment description



In this experiment the behaviour of the comparator is studied.

A voltage U_1 (=U_N), which can be adjusted with the potentiometer R_2 in experiment field 1 (EF1), is applied to the inverting input and a voltage U_{FG} (=U_P) to the non- inverting input via the function generator (FG). The voltage U_1 is measured with multimeter 1 (MM1) and the output voltage of the OPA with MM2. The voltage U_{FG} can be adjusted at the function generator, and its value can be read there. The output voltage is observed for several ratios of U_1 (=U_N) and U_{FG} (=U_P).

1.6 Result



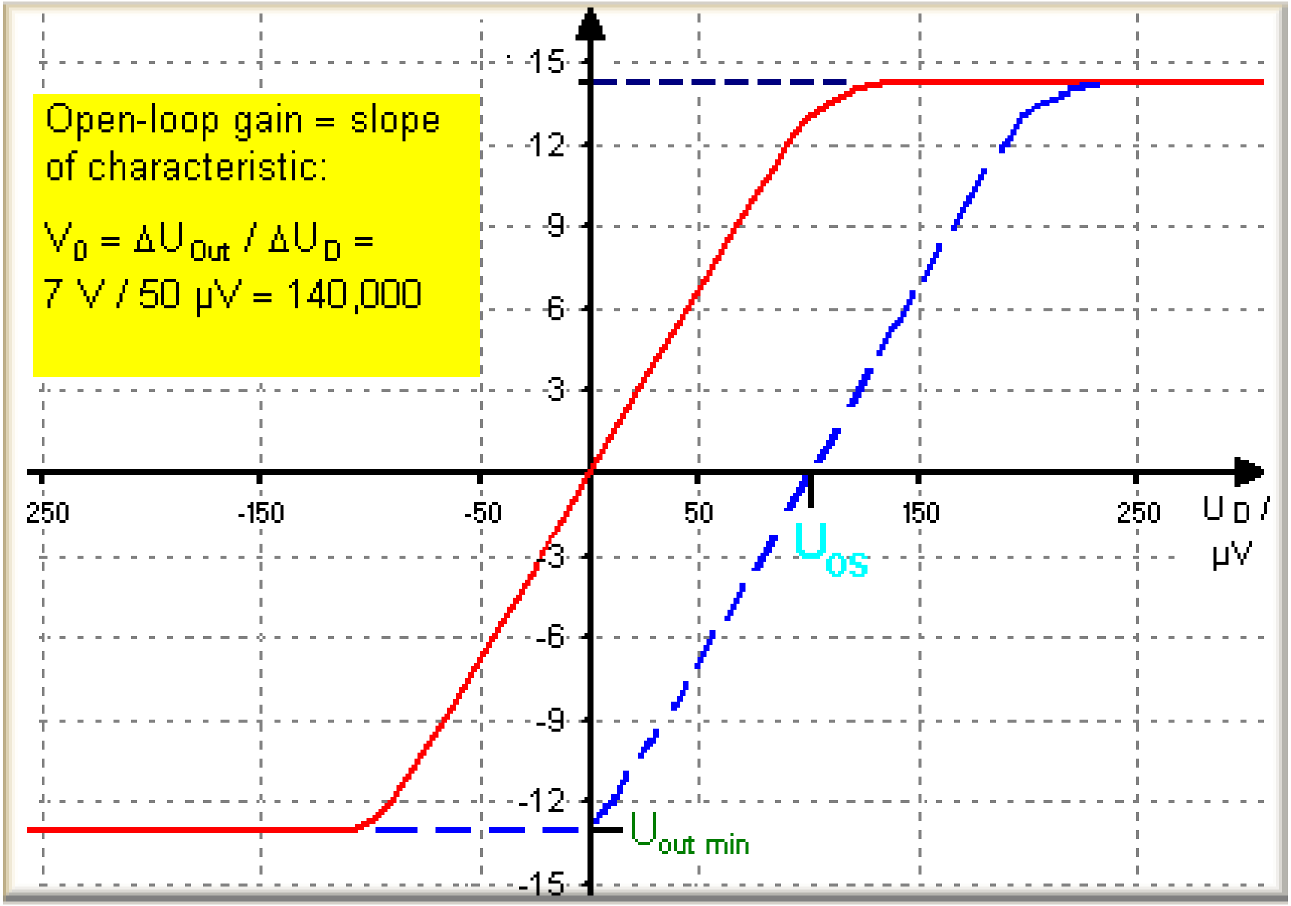
The result confirms what has been stated above.

If $U_P > U_N$, the output voltage is positive, if, on the other hand, $U_P < U_N$, the output voltage is negative. If the two voltages U_N ($=U_1$) and U_P ($=U_{FG}$) are set to the same value, the output voltage will be either positive or negative, depending on the so-called offset voltage[1] , which results from dissymmetries in the internal structure of the OPA.

[1] **Offset Voltage**

Many IC operational amplifiers have contact pins for an offset voltage compensation. The offset can be shifted by means of an externally connected potentiometer.

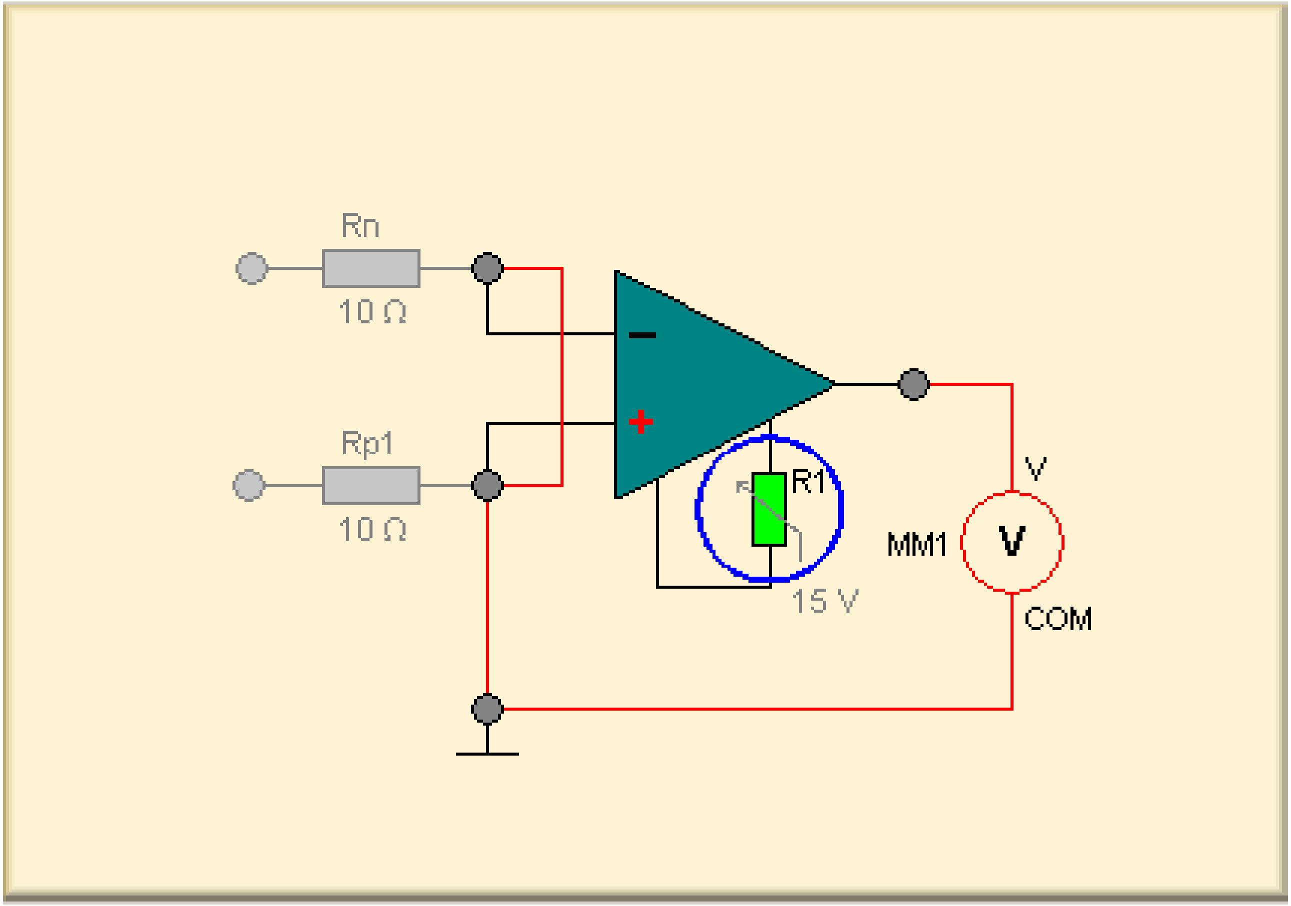
1.7 Offset voltage



One of the undesirable features of the operational amplifier is the offset voltage (U_{OS}). It results from dissymmetries among the internal components (structure, design). The offset voltage reaches the output with the open-loop gain (V_0). If the difference voltage at the inputs is zero, the output voltage itself is therefore not zero, but takes a positive or negative value depending on the components. The offset voltage has its most distorting effect when small direct voltages are amplified.

Red curve: characteristic without offset.
Blue curve: characteristic with offset.

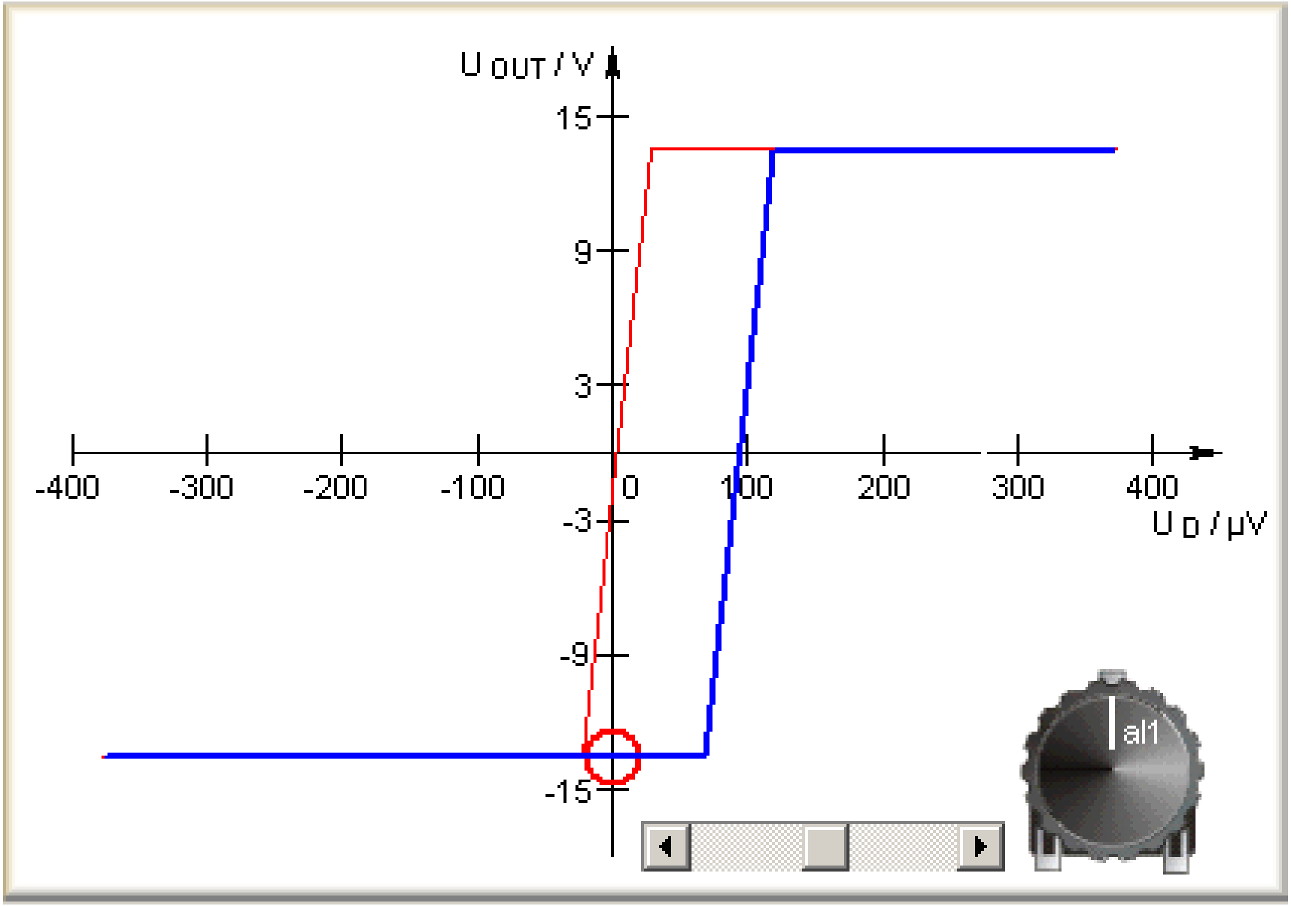
1.8 Carrying out the experiment



Many ICs of operational amplifiers have connections for compensating the offset by external elements. In EF1 the offset can be compensated with the resistor R_1.

In this experiment, the output voltage is measured while the two inputs of the OPA are connected to the reference potential ($U_D = 0$). By varying R_1 the offset of the OPA is varied and the effect on the output voltage is studied.

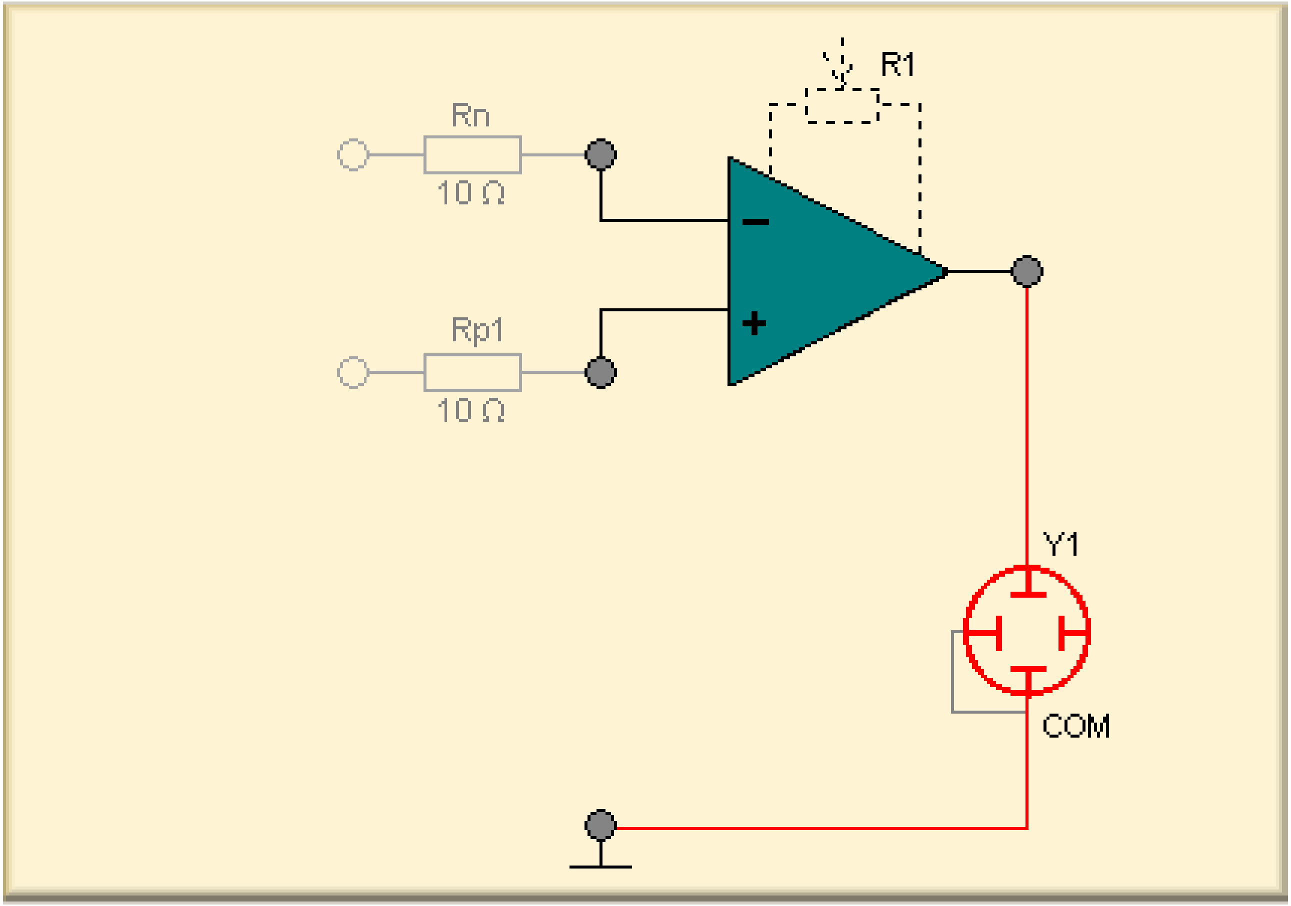
1.9 Evaluation



There is a position where the polarity of the output voltage changes either from positive to negative values or vice versa.

As is shown in the animation, the offset of the OPA can be changed with R_1 (this corresponds to shifting the transfer characteristic of the OPA). This leads to varying output voltages for $U_D = 0$ (intersection with the y-axis).

1.10 Common-mode rejection



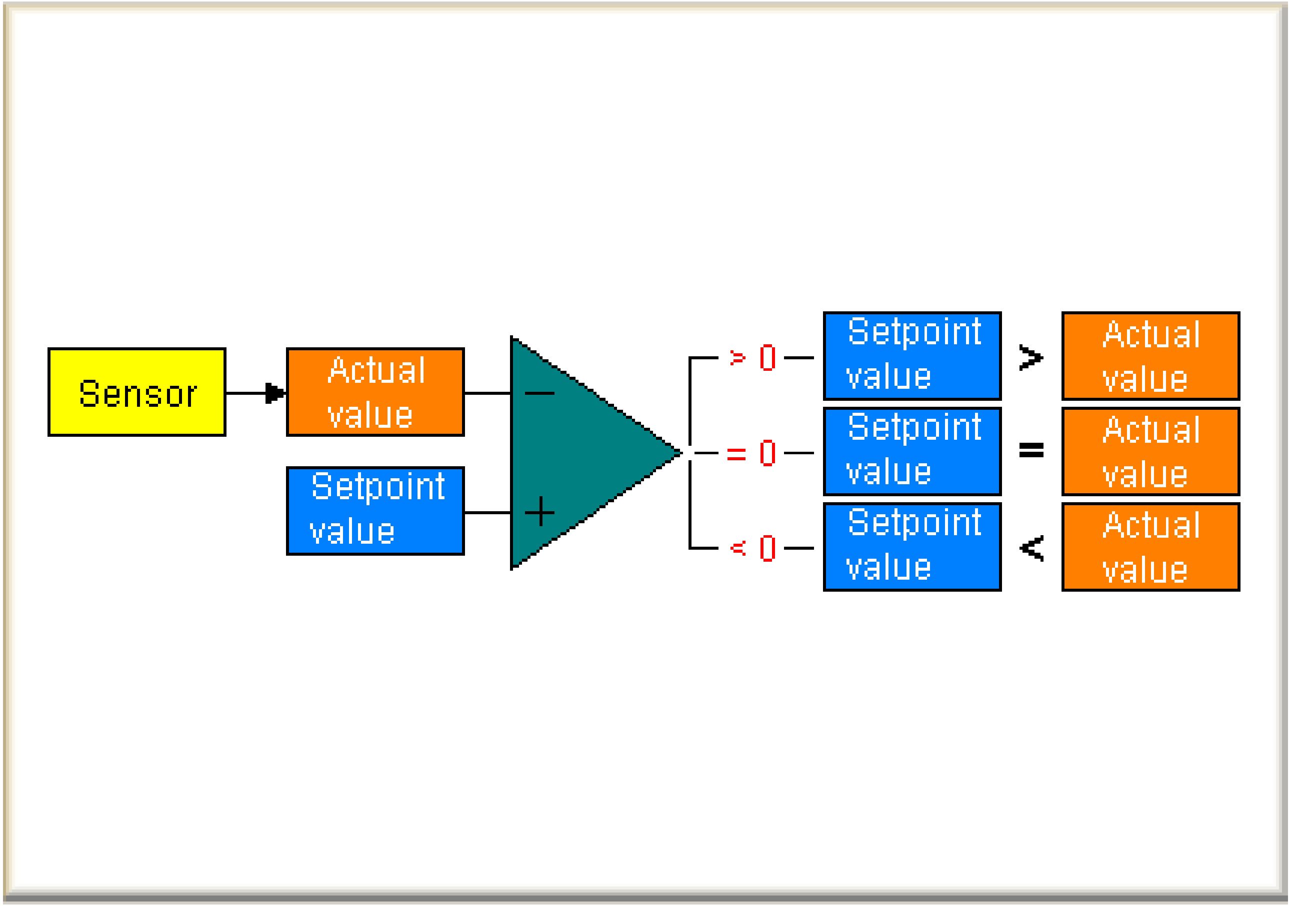
In the case of a difference amplifier, only the difference between the two input signals is relevant. Components that are equal in both signals (common mode) cancel in the difference and are thus suppressed by the difference amplifier.

If the same signal is applied to both inputs, the difference voltage is zero. Because of the above mentioned offset voltage[1] the output voltage then is positive or negative. The effect of common-mode rejection is used, e.g., for filtering equal components from two signals.

[1] **Offset Voltage**

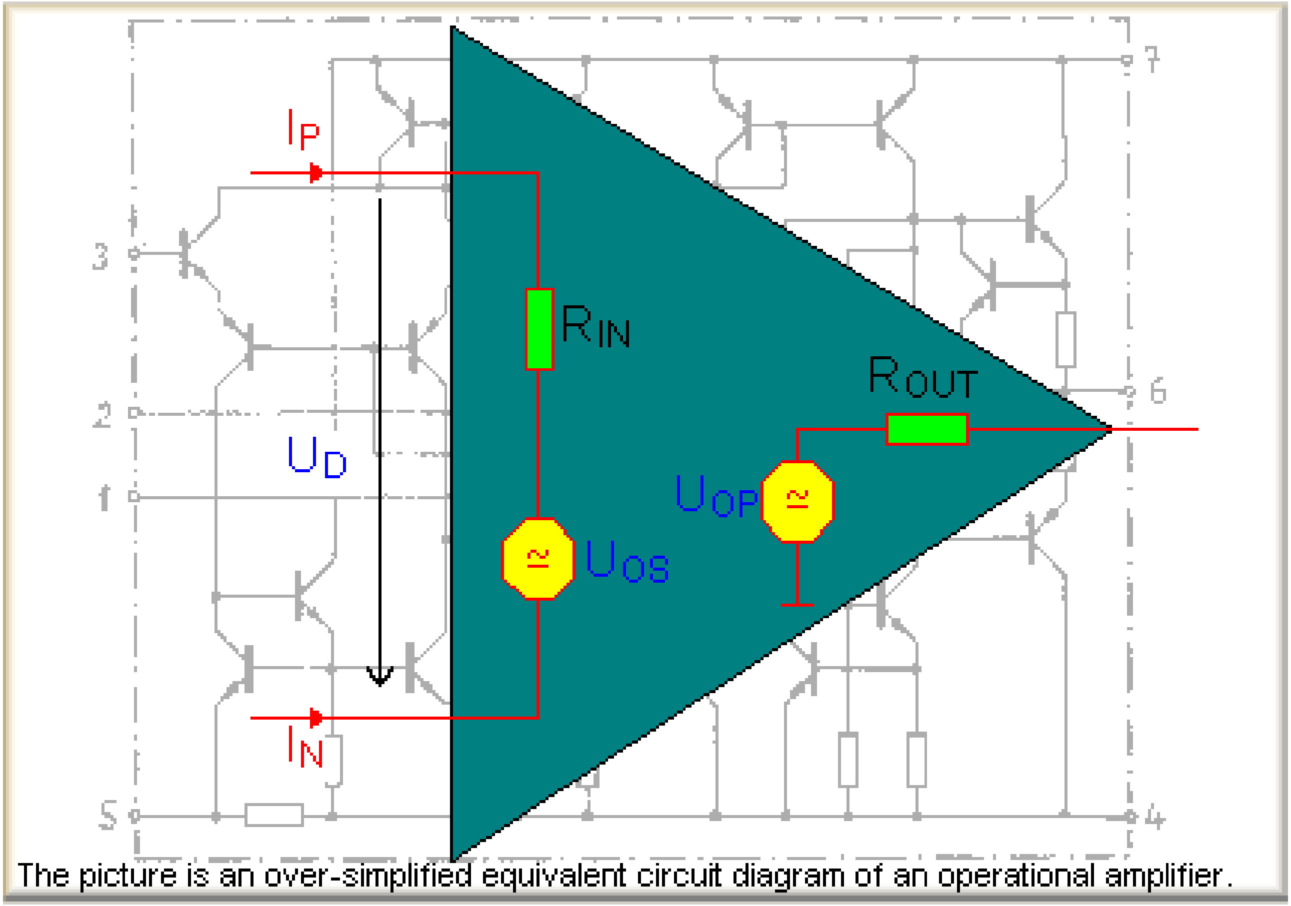
Many IC operational amplifiers have contact pins for an offset voltage compensation. The offset can be shifted by means of an externally connected potentiometer.

1.11 Application



Comparators are used, e.g., for comparing a signal with a setpoint value. If the signal deviates from the setpoint value, the output voltage is positive or negative depending on the external circuit elements and the deviation. The output voltage is changed even by the slightest deviations. In the picture the ideal case is shown, the offset not being taken into account.

2.1 Introduction



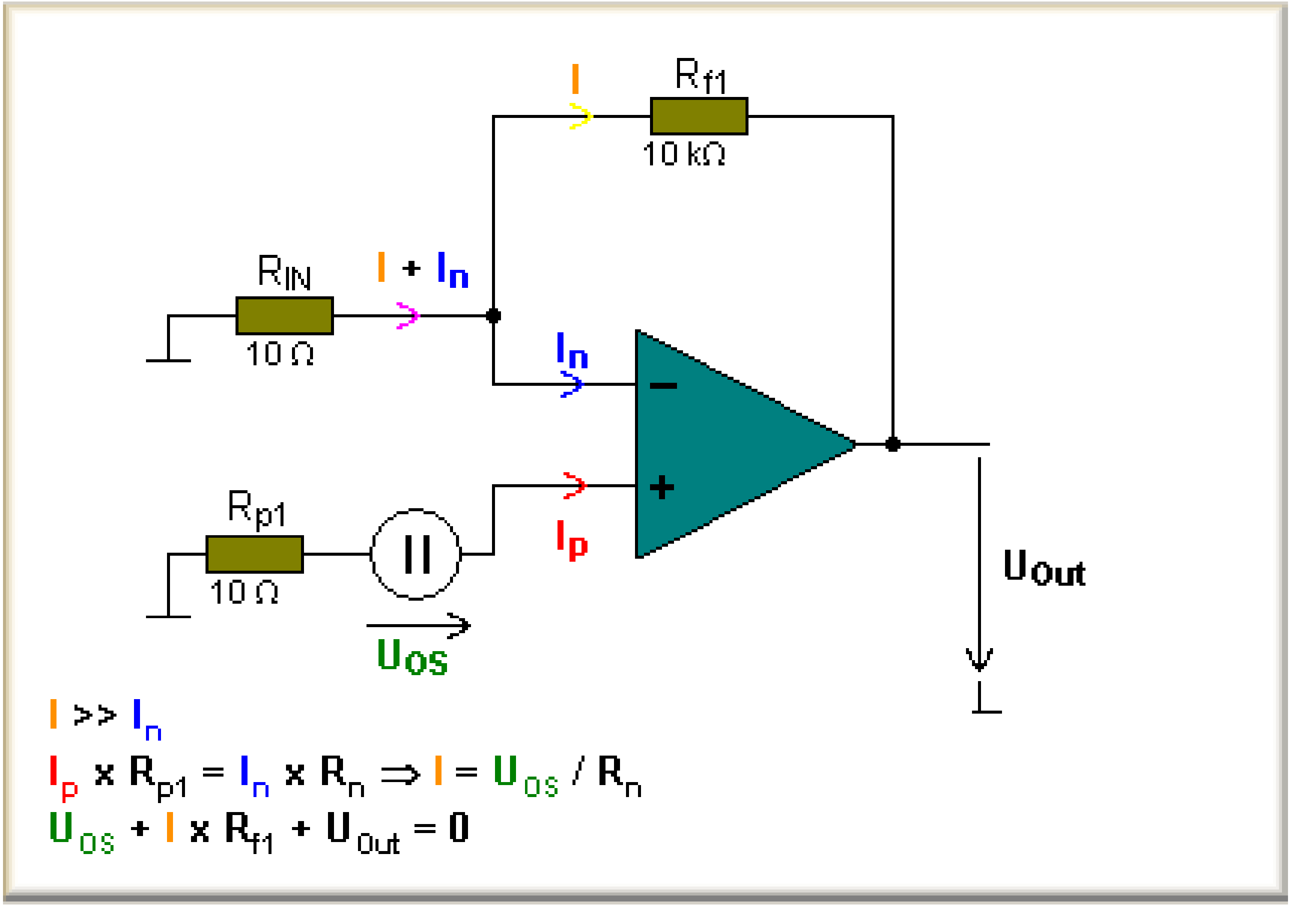
The picture is an over-simplified equivalent circuit diagram of an operational amplifier.

The following chapter deals with the characteristics of an operational amplifier. The circuits for measuring the characteristic quantities are shown.

The characteristic quantities include:

- offset voltage
- positive input current I_p
- negative input current I_n
- input bias current
- input offset current
- input resistance R_{in}
- slew rate SR

2.2 Offset voltage and offset compensation



The offset voltage[1] is the input difference voltage at which the output voltage is 0 V.

As the offset voltage U_{OV} is very small, the output voltage is measured in this experiment. The offset voltage is determined via the operating gain. With the assumption that the bias currents are equal ($I_p = I_n$) or that R_n and R_{p1} small, the following relations hold:

$$U_{OS} \cong -\frac{U_{out}}{1+\frac{R_{f1}}{R_n}}$$

$$U_{OS} \cong -\frac{R_n}{R_{f1}} \cdot U_{out}$$

with

$$R_n = R_{p1} = 10\Omega$$

$$R_{f1} = 10k\Omega$$

it follows that

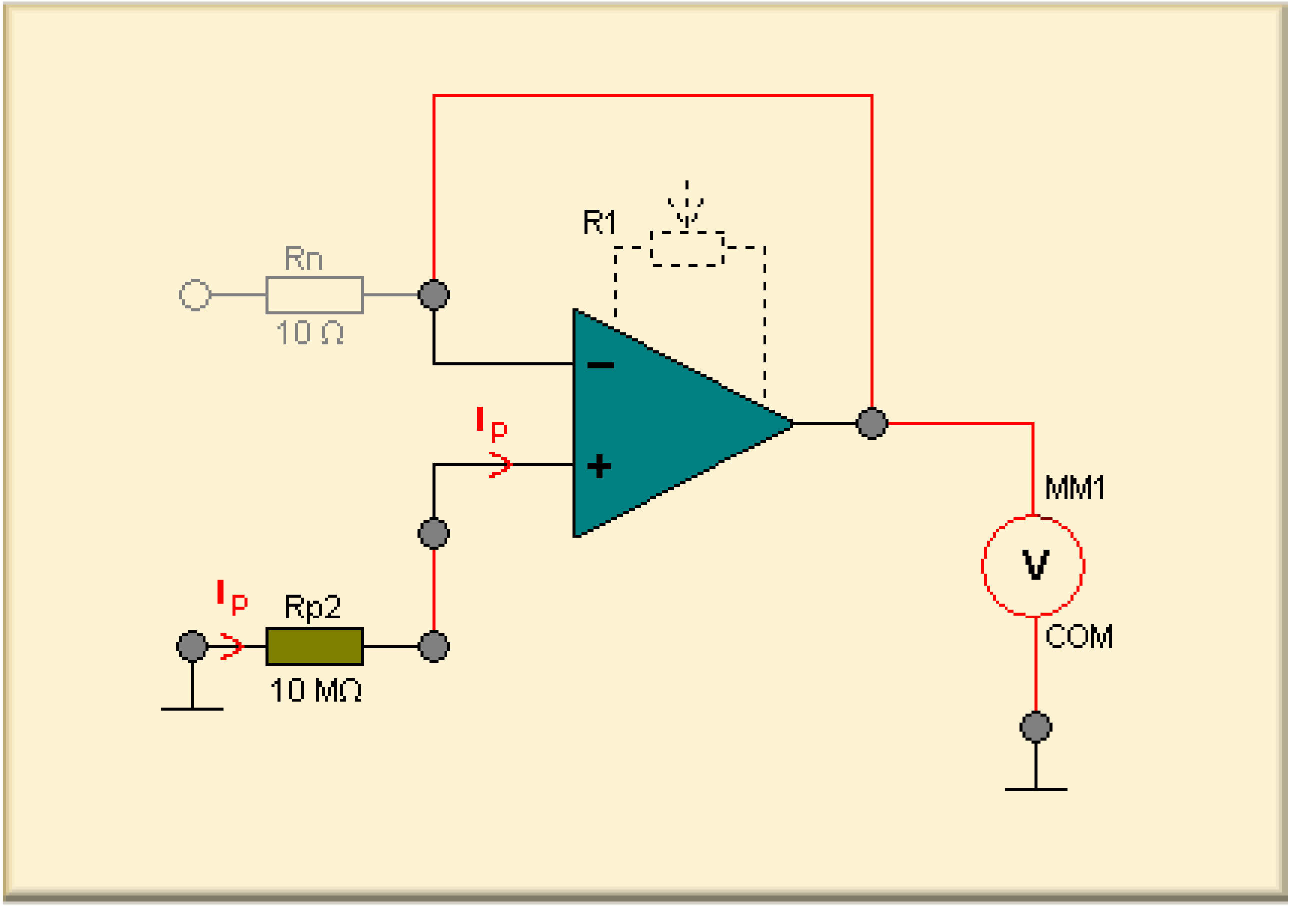
$$U_{OS} \cong -\frac{U_{out}}{1000}$$

---

[1] **Offset Voltage**

Many IC operational amplifiers have contact pins for an offset voltage compensation. The offset can be shifted by means of an externally connected potentiometer.

2.3 Positive input current



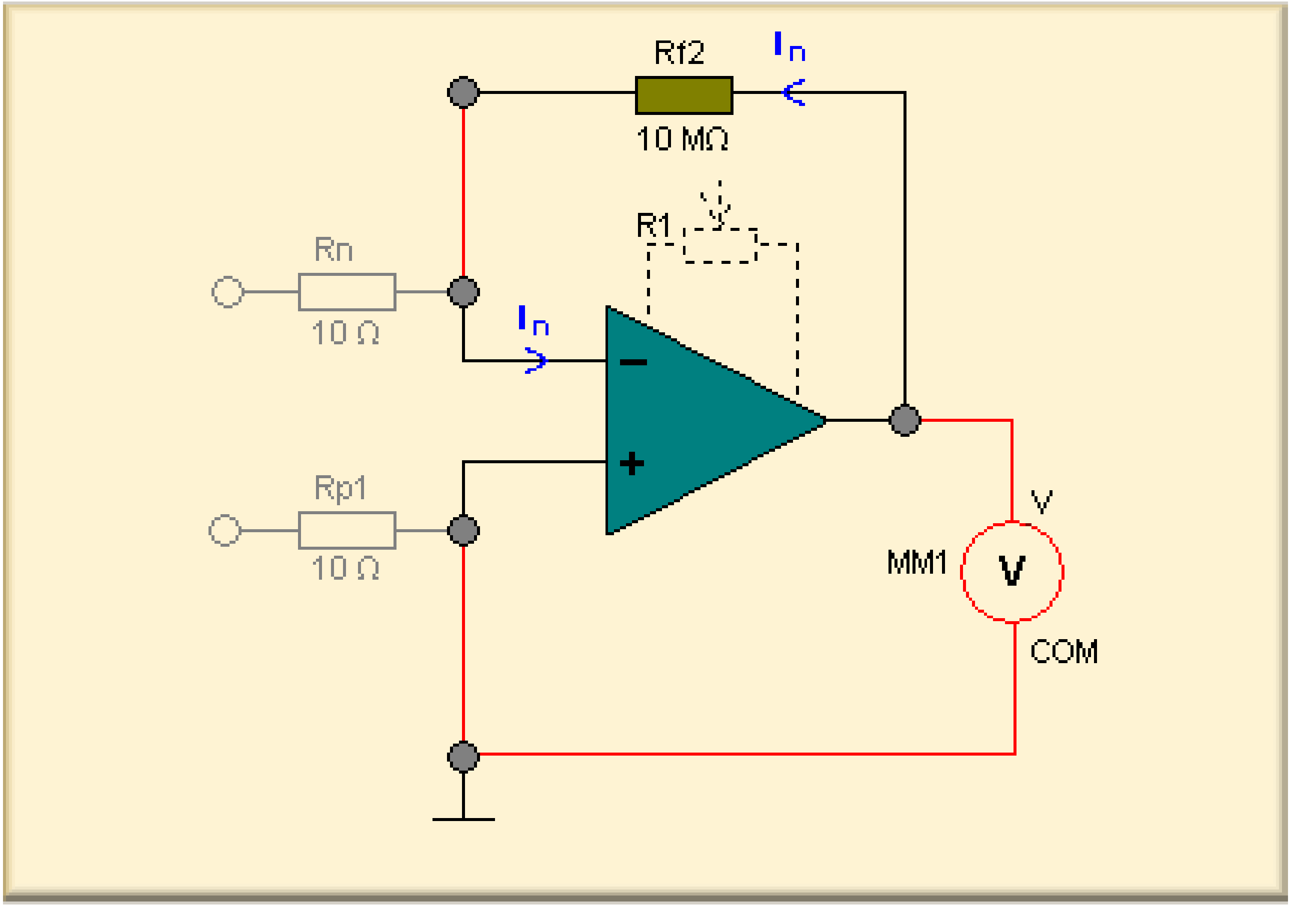
The positive input current is the current that flows through the non-inverting input. It cannot be measured directly because it is in of the order of magnitude of nA. There is a voltage drop at R_{p2} due to the input current. The gain is 1 because there are no resistances in the feedback. We have $U_{out} = -U_{rp2}$. The positive input current therefore is:

$$I_p = -\frac{U_{out}}{R_{p2}}$$

with

$$R_{p2} = 10\ M\Omega$$

2.4 Negative input current



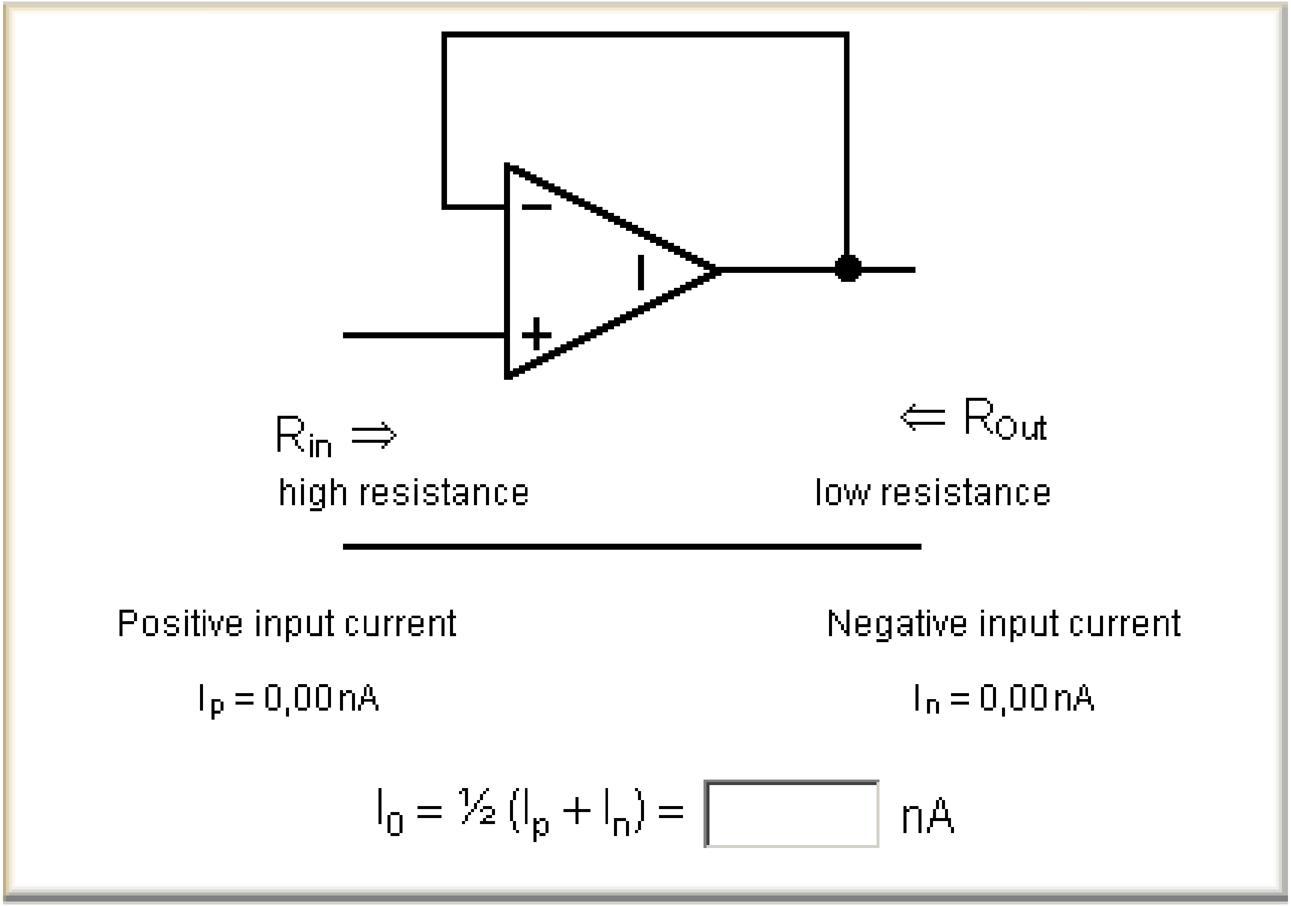
The negative input current is the current that flows through the inverting input. In cannot be measured directly because it is of the order of magnitude of nA. There is a voltage drop at R_{f2} due to the input current. As the inverting input is Virtually grounded ($U_D = 0$), we have $U_{out} = +U_{rf2}$. The negative input current therefore is:

$$I_n = +\frac{U_{out}}{R_{f2}}$$

with

$$R_{f2} = 10\ M\Omega$$

2.5 Input bias current



Positive input current

$I_p = 0{,}00\,nA$

Negative input current

$I_n = 0{,}00\,nA$

$I_0 = ½ (I_p + I_n) = \square$ nA

The input bias current I_0 is the mean value of the positive and negative input current:

$$I_0 = \frac{1}{2}\left(I_p + I_n\right)$$

Because of its low input current an operational amplifier can also be used as an impedance transformer[1] by generating a gain of 1 via the feedback. Thereby the operational amplifier makes the input signal available at its output in a low-resistance source.

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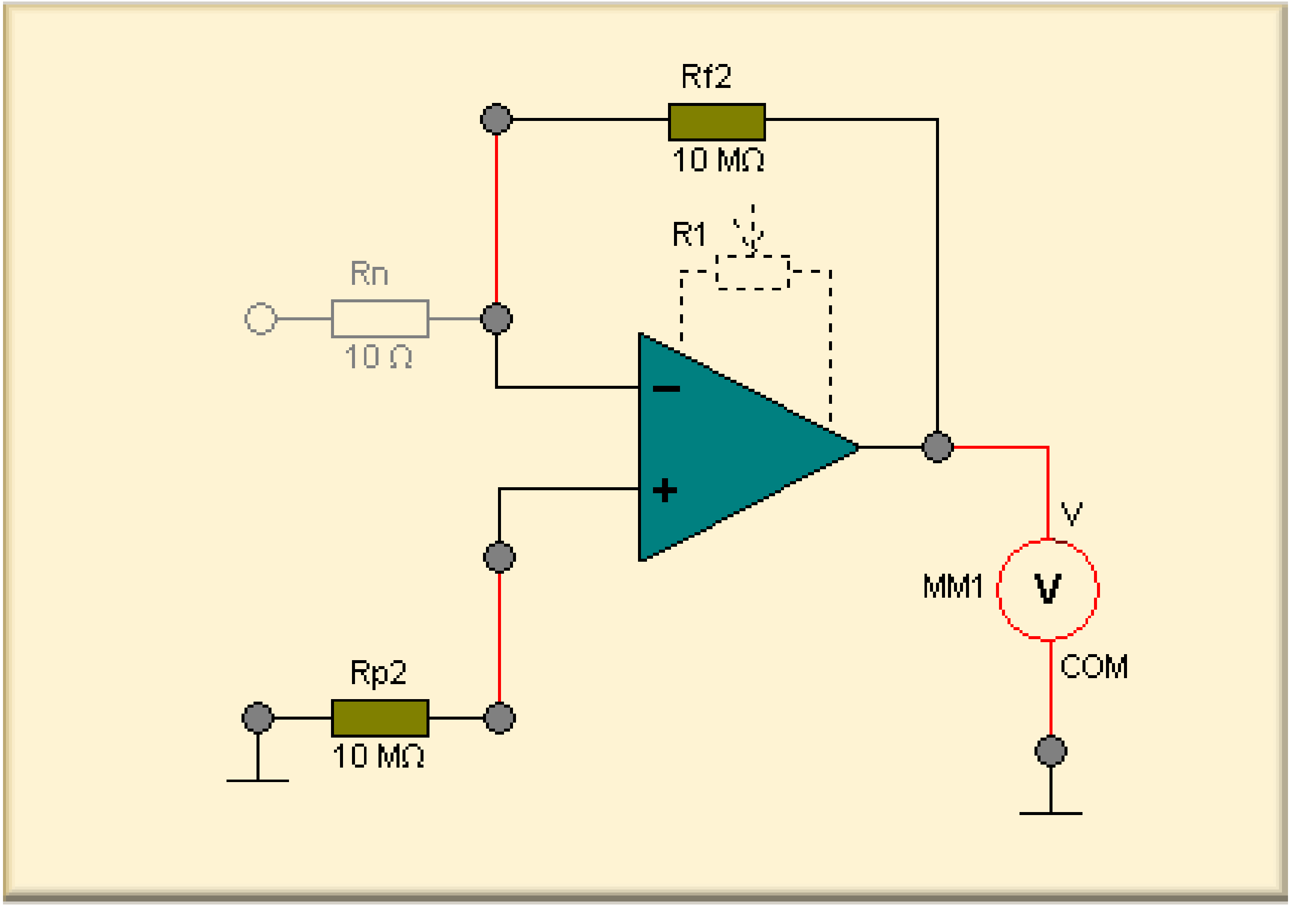
[1] **Impedance Transformer**

An impedance transformer serves to match a high-impedance generator with a low- impedance load. The input and output voltage are equal and in phase.

2.6 Input offset current



The input offset current I_{OC} is the difference between the positive and the negative input current. The offset voltage is caused by the input current in conjunction with the input resistance.

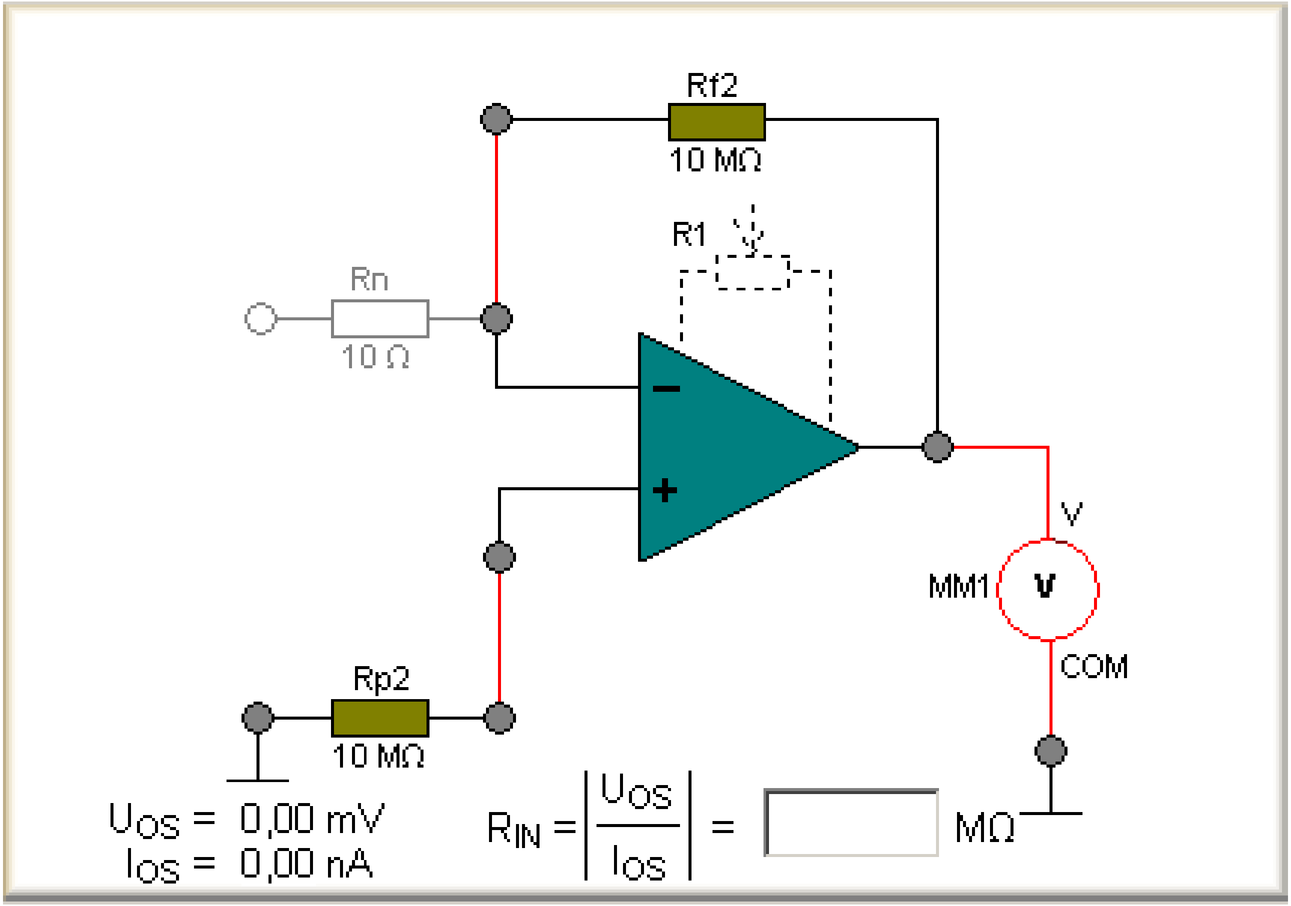
With $R_{f2} = R_{p2}$ we have:

$$I_{OS} = |I_n| - |I_p|$$

and

$$I_{OS} = \frac{U_{out}}{R_{f2}} = \frac{U_{out}}{R_{p2}}$$

2.7 Input resistance

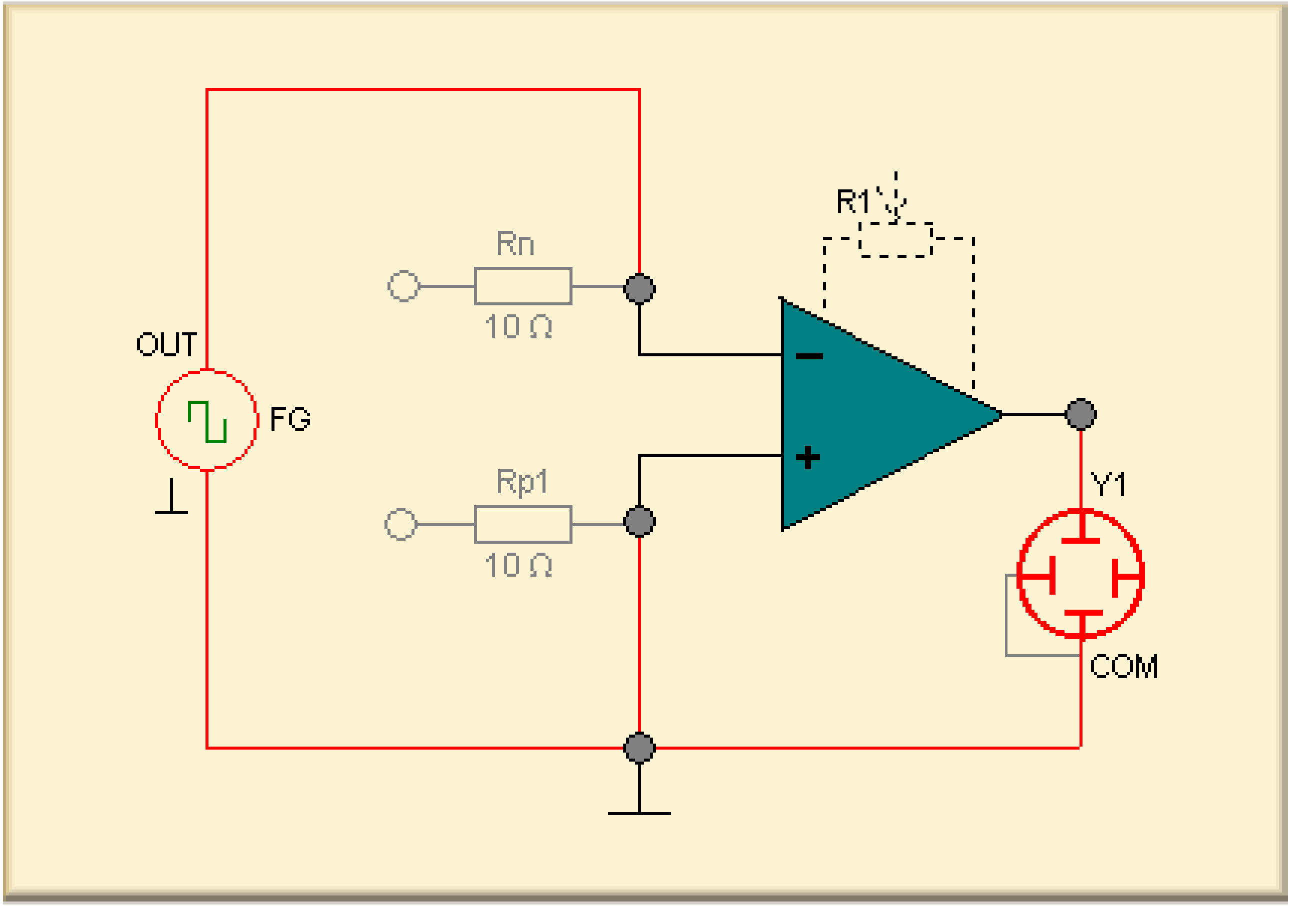


Operational amplifiers have a very high input resistance. The offset voltage is caused by the input resistance in conjunction with the input offset current. Because of the high input resistance and the low output resistance it is possible to set up an impedance transformer[1] with an OPA circuit.

[1] **Impedance Transformer**

An impedance transformer serves to match a high-impedance generator with a low- impedance load. The input and output voltage are equal and in phase.

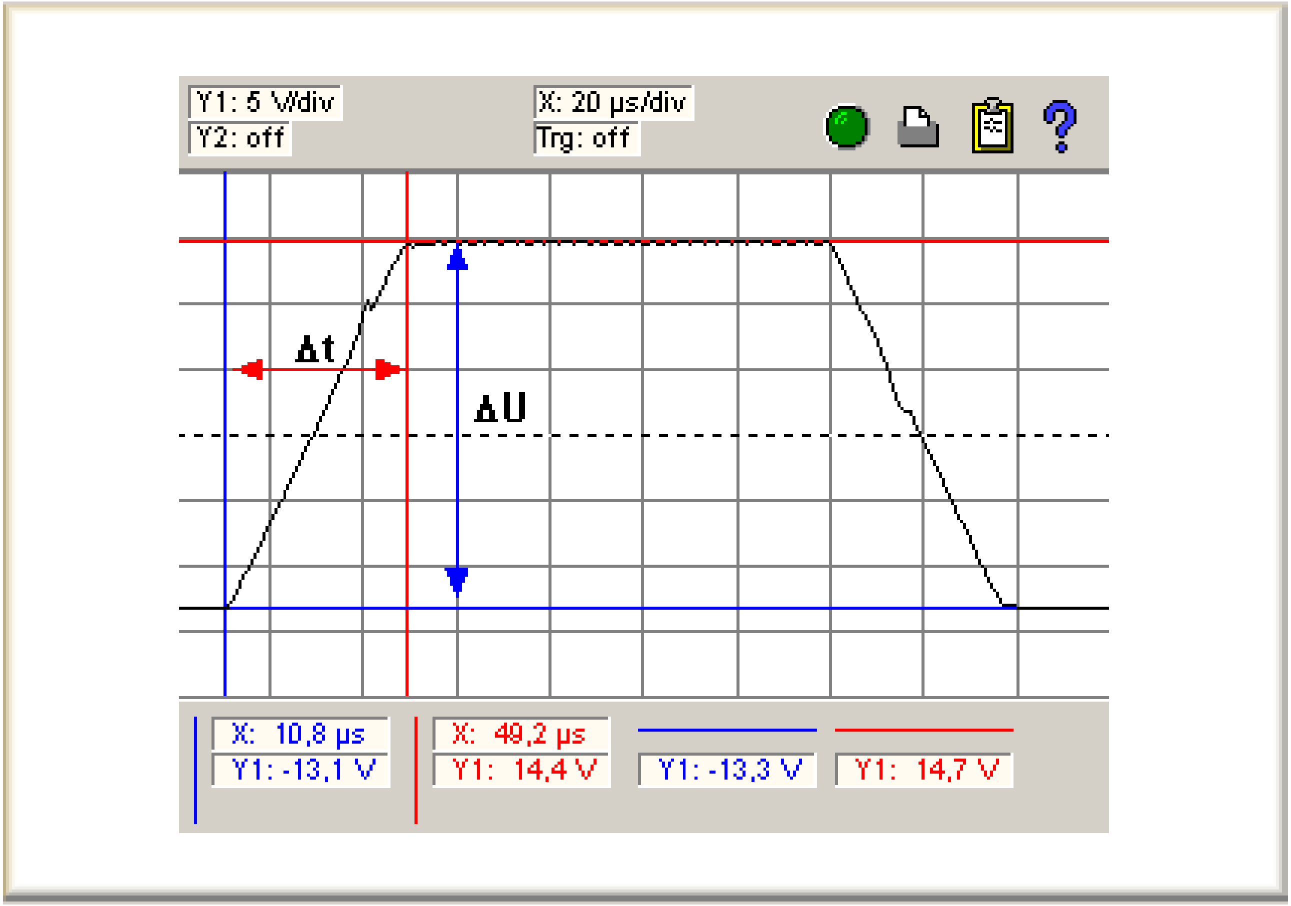
2.8 Slew rate



If the input signal at the OPA changes as a function of time, the output signal will follow it. However, due to internal capacitances this response cannot take place at an arbitrary rate. The slew rate (SR) is the maximum steepness of the leading edge of the output voltage. It is a measure for the switching speed of an operational amplifier. Its is given in units of **V/µs**.

A desired output signal can be achieved only if its maximum steepness does not exceed the SR.

2.9 Evaluation SR



Y1: 5 V/div
Y2: off
X: 20 µs/div
Trg: off

X: 10,8 µs
Y1: -13,1 V

X: 49,2 µs
Y1: 14,4 V

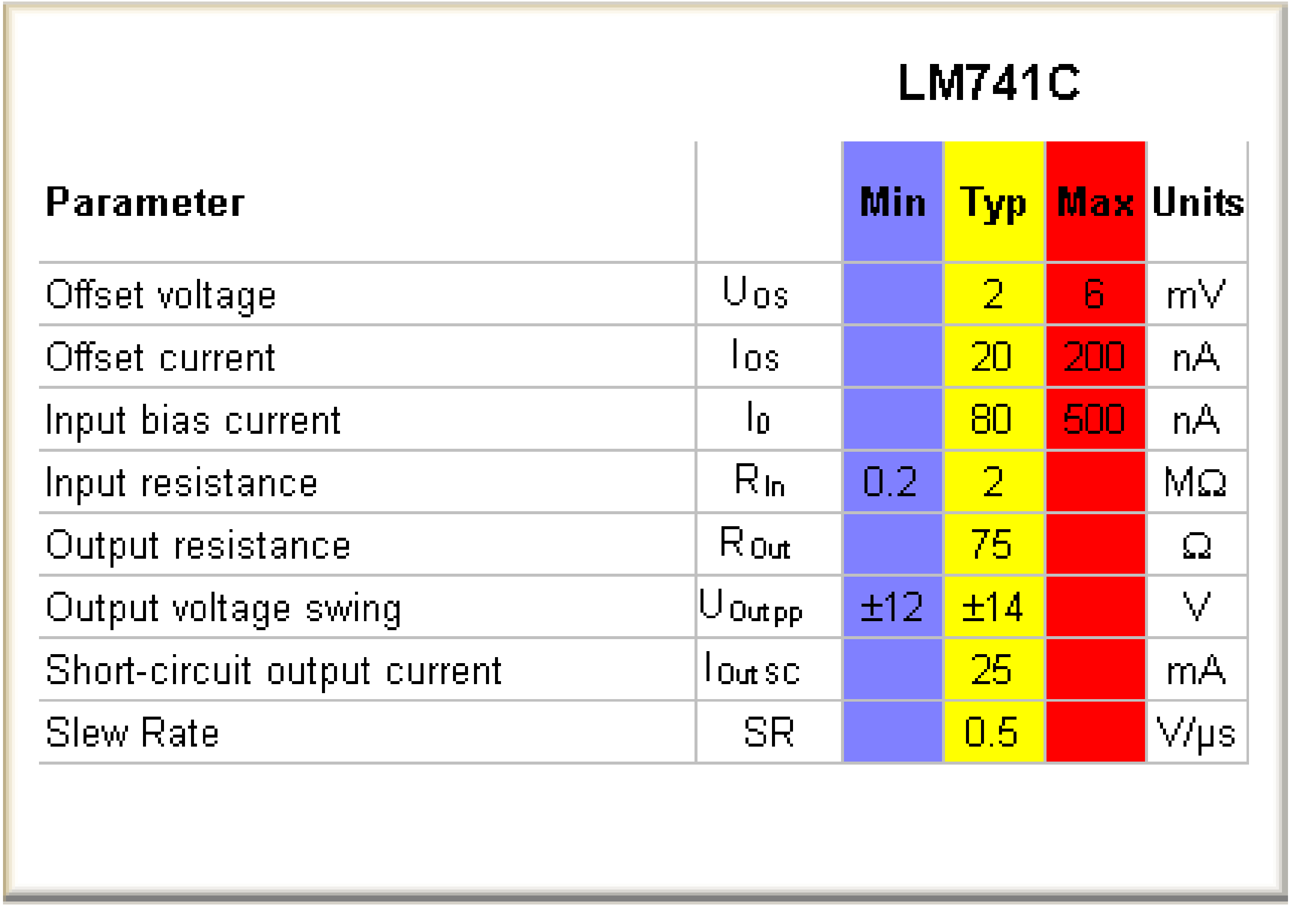
Y1: -13,3 V

Y1: 14,7 V

The shape of the signal you obtained in the previous experiment should approximately look like this one.

The co-ordinates of the two "corners" were determined with the markers. The slew rate is obtained from the divided difference ΔU / Δt.

2.10 Summary



LM741C

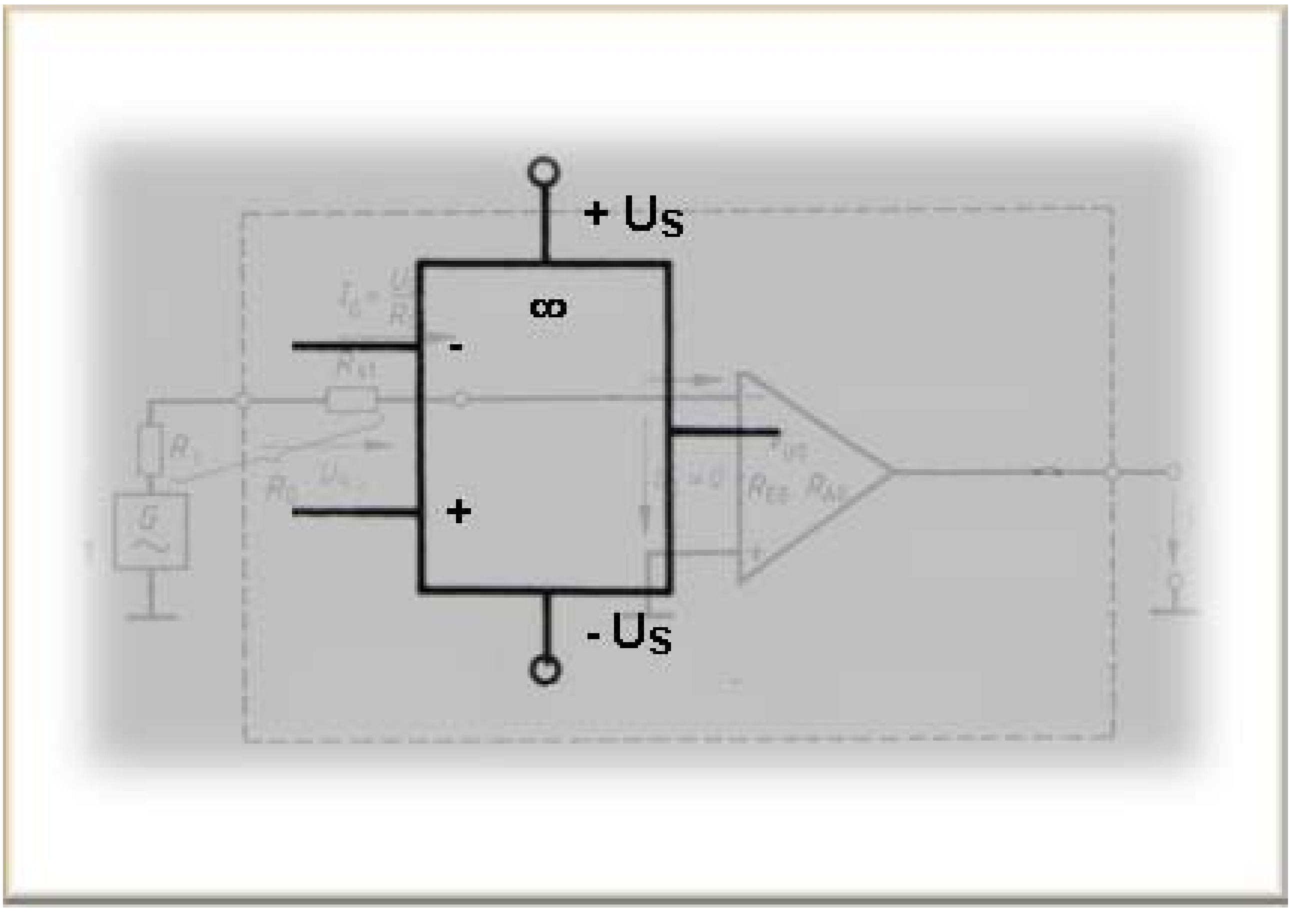
Parameter		Min	Typ	Max	Units
Offset voltage	U_{os}		2	6	mV
Offset current	I_{os}		20	200	nA
Input bias current	I_0		80	500	nA
Input resistance	R_{In}	0.2	2		MΩ
Output resistance	R_{Out}		75		Ω
Output voltage swing	$U_{Out\,pp}$	±12	±14		V
Short-circuit output current	$I_{Out\,sc}$		25		mA
Slew Rate	SR		0.5		V/µs

Variations in the process of manufacturing OPAs lead to broad variance of the values determined in this chapter. Therefore these values may vary considerably between different boards. For example the minimum offset voltage can be near 0 V.

In the table the values of the data sheet of the LM741 are shown.

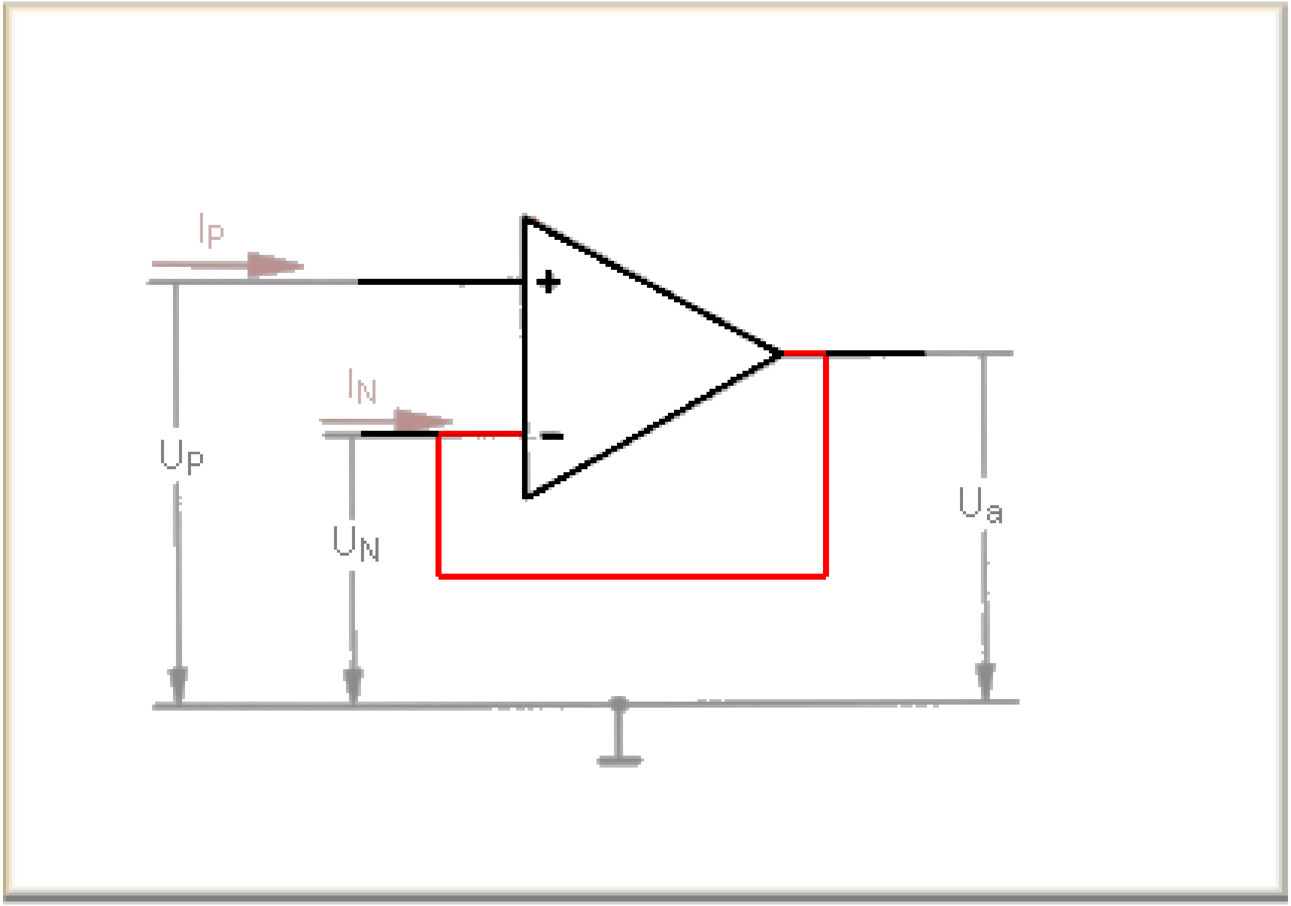
Note that the parameters depend on the temperature and on the load, i.e. on the output current. In the experiments carried out here the parameters were determined without an additional load.

3.1 Introduction



In the case of an inverting operational amplifier the signal to be amplified is fed into the **inverting** input. Therefore the output and input voltage have opposite signs.

3.2 Negative feedback



By negative feedback part of the output voltage is led back to the inverting input. This leads to a damping of the gain.

There is always a negative feedback in amplifier circuits in order to counteract an oscillation caused by positive feedback[1] .

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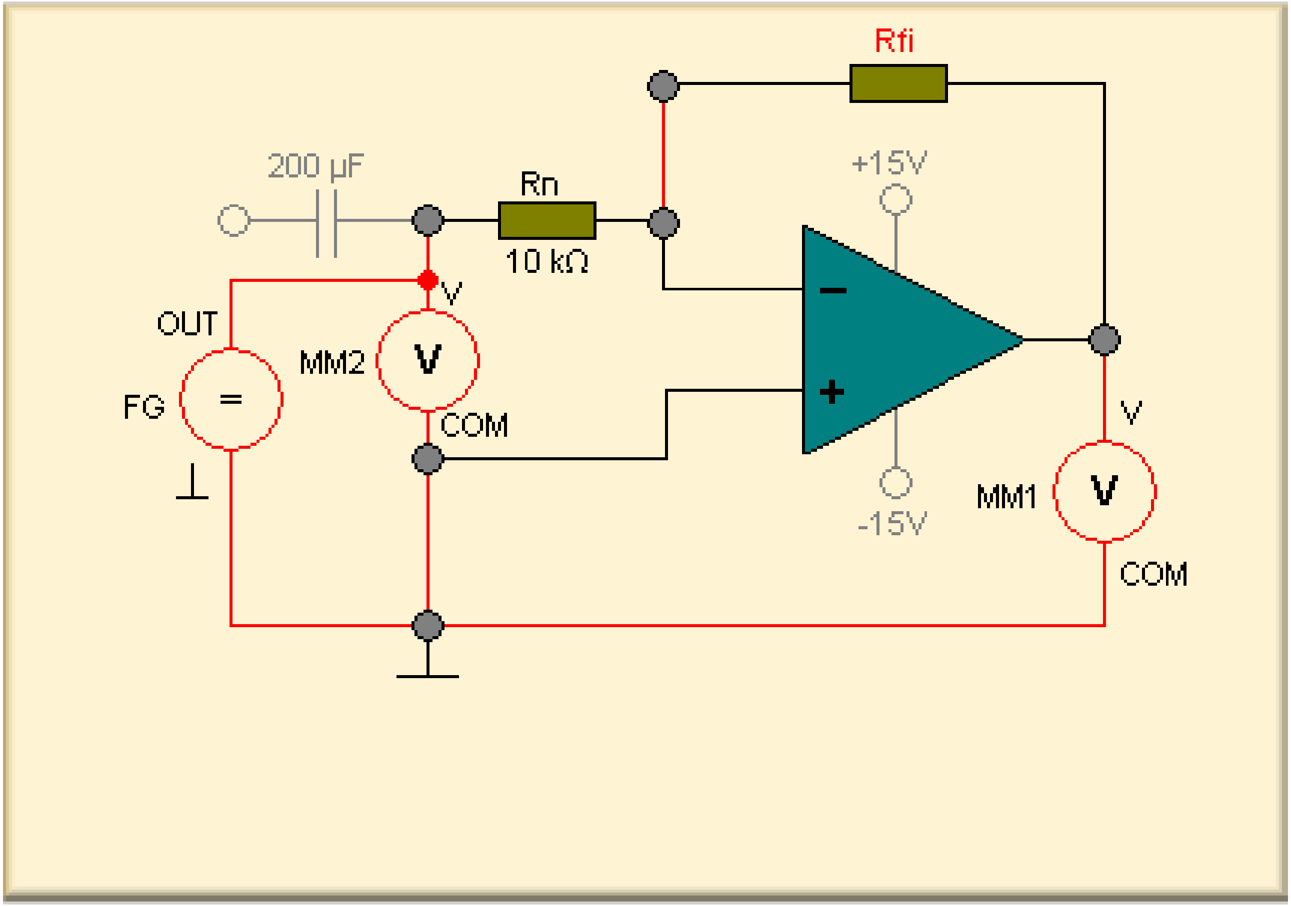
[1] **Positive Feedback**

A positive feedback connects part of the output voltage back to the non- inverting input, which, in most cases, immediately leads to oscillations of an amplifier circuit. This effect is well known from acoustic feedback (microphone directly in front of the loudspeaker).

3.3 Gain



The gain is the ratio of the output voltage and the input voltage:

$$V_u = \frac{U_{out}}{U_{in}}$$

Usually the gain is given in the logarithmic ratio units of decibel[1] (dB):

$$v_u = 20 \cdot \log\left(\left|\frac{U_{out}}{U_{in}}\right|\right)$$

$$v_u = 20 \cdot \log\left(\left|V_u\right|\right)$$

The frequency dependence of the gain is called the transfer function[2] .

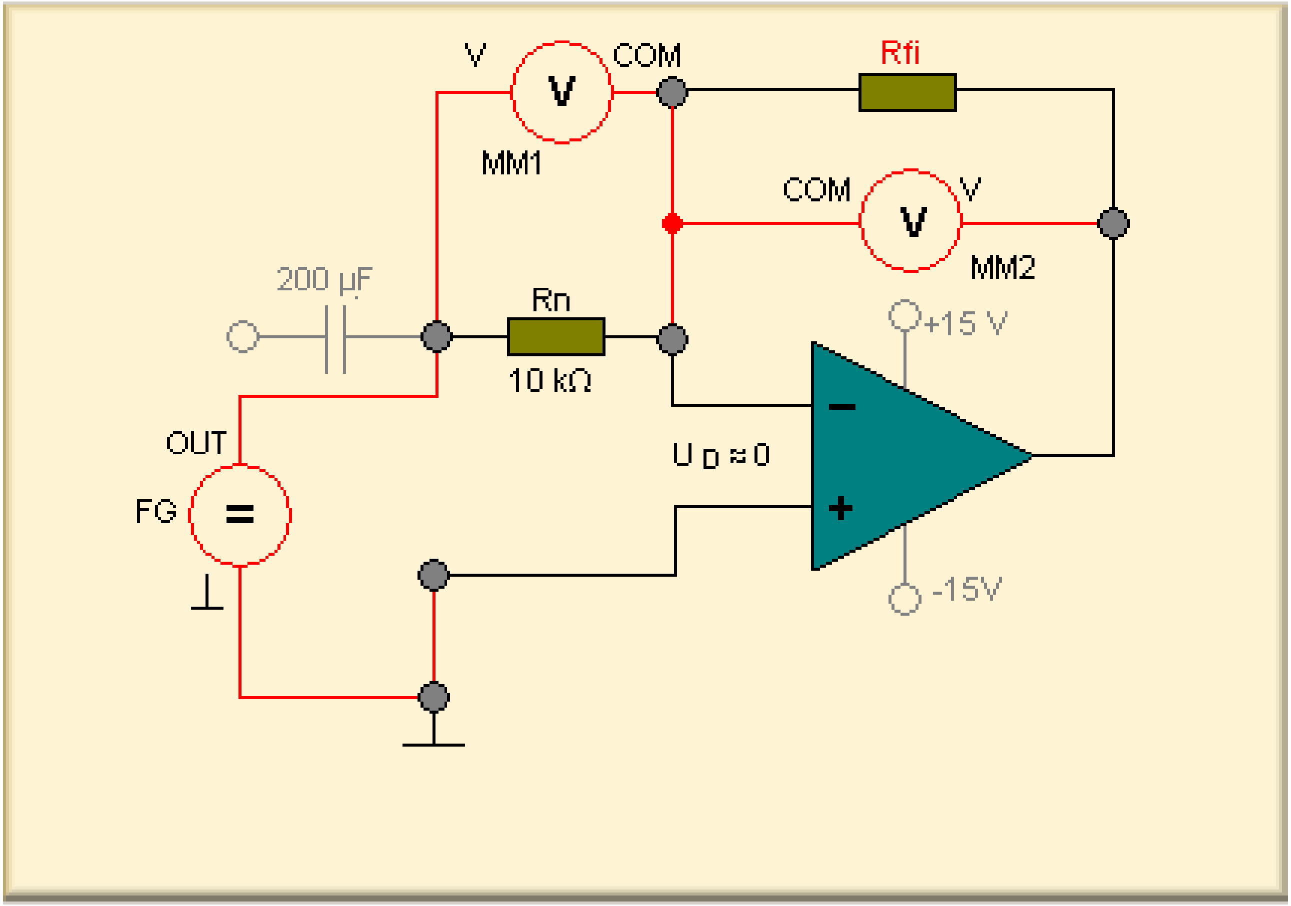
[1] **Decibel**

Named after the American physiologist A. G. Bel. The logarithmic scales make it easier to perform calculations with very large and very small numbers. In natural sciences, large ranges of values can only be represented convincingly if logarithmic scales are used. Moreover, multiplication is turned into addition by the logarithms. Thus the total gain of two series-connected amplifiers is given by the sum of the two dB values of the individual gains.

[2] **Transfer Function**

The transfer function describes the ratio of the output and input signals at various frequencies in a linear system. It provides the mathematical description of a system's function.

3.4 Formula for the voltage gain



Because of the low difference input voltage the inverting input is almost grounded. That means the voltage drop at R_n corresponds to the input voltage and the voltage drop at R_{f1} to the output voltage. The gain therefore is:

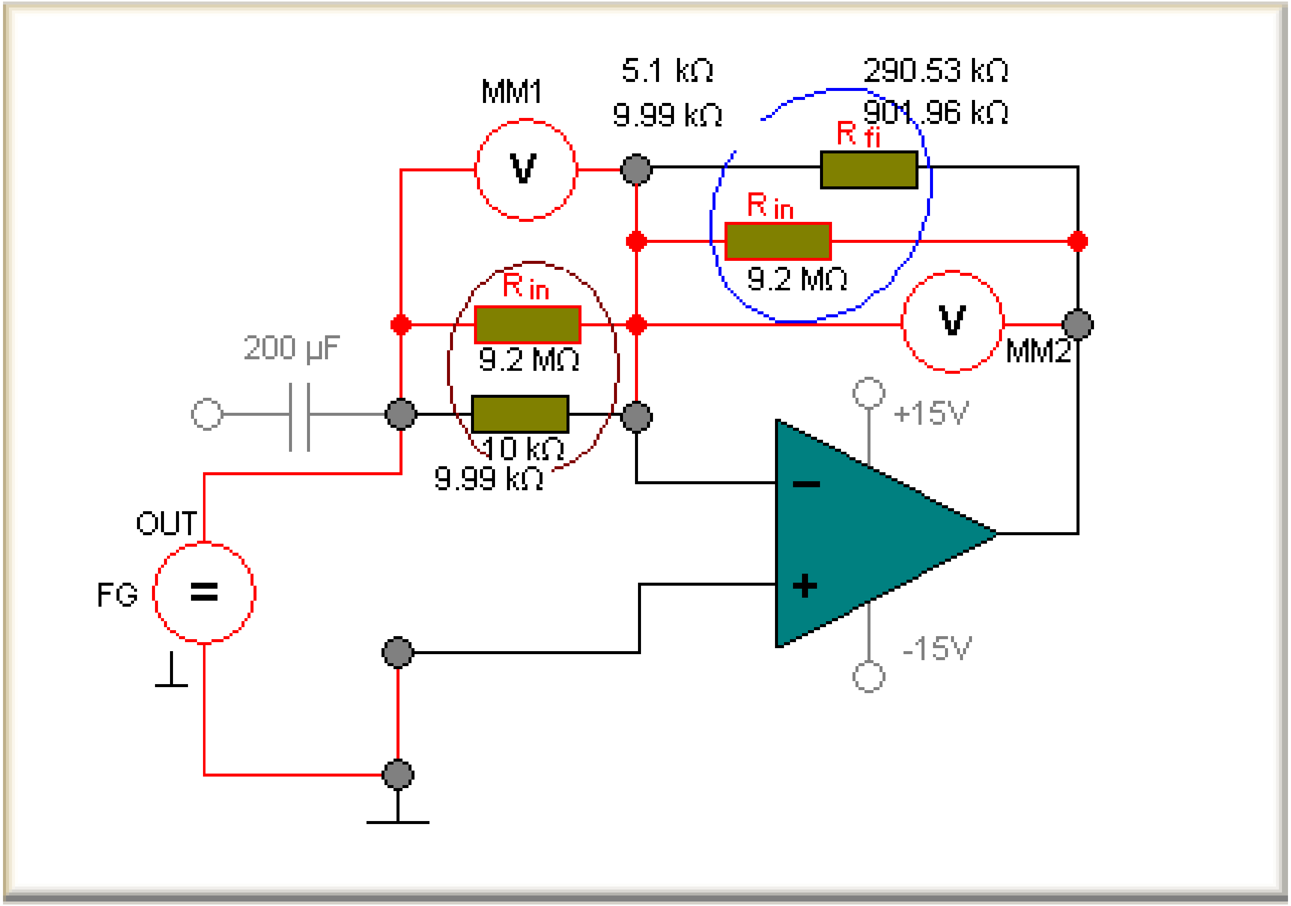
$$V_u = \frac{U_{out}}{U_{in}}$$

$$= \frac{U_{Rfi}}{U_{Rn}} = -\frac{R_{fi}}{R_n}$$

with

R_n = 10 kΩ
R_{fi} = (5.1 kΩ; 10 kΩ; 300 kΩ; 1 MΩ)

3.5 Result



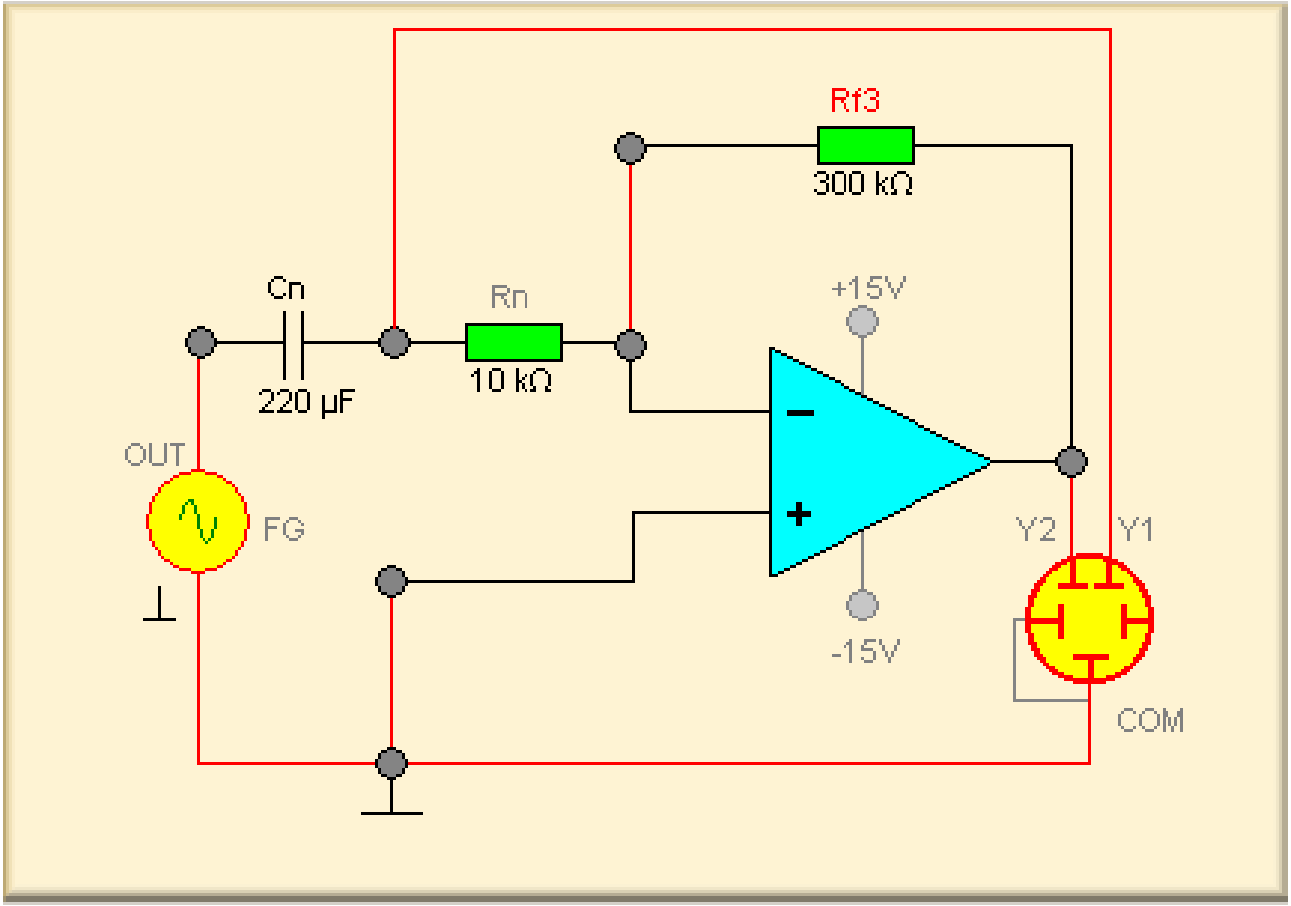
According to the theory the gains should be equal in both experiments. For higher gains this is not the case here because of the internal resistance of the multimeter (real multimeters[1]). The internal resistance of the multimeter is connected in parallel to the feedback resistance R_{fi}, which results in a reduction of the feedback resistance and of the gain.

The internal resistance of the multimeters is approx. 9.2 MΩ. Therefore the gain is reduced from 100 to approximately 90 in the case of R_{f4}.

[1] **Real Multimeters**

An ideal voltmeter would have an infinitely high internal resistance. Thus no current would flow through it, and it would not influence the voltages and currents in the circuit. However, a real voltmeter has a high, but still finite internal resistance. Therefore a certain current flows through it so that voltages and currents in the circuit are changed.

3.6 Amplitude-frequency response



Internal capacitances lead to a reduction of the gain with increasing frequency. At the cutoff frequency[1] the gain of the OPA has fallen by a factor of $1/\sqrt{2} \approx 0{,}707\ (\hat{=}\ 3dB\ )$ compared with its maximum value. Without frequency dependent external circuit elements, the OPA has its maximum gain in the case of direct voltage.

Another important quantity is the transition frequency[2] .

Please read the remark on the frequency response[3] .

[1] **Cutoff Frequency**

The cutoff frequency is the frequency at which the magnitude of the transfer function has fallen by –3 dB (a factor of 0.707 = 1 / √2) compared with its maximum value. Therefore it is also called 3-dB-cutoff frequency.

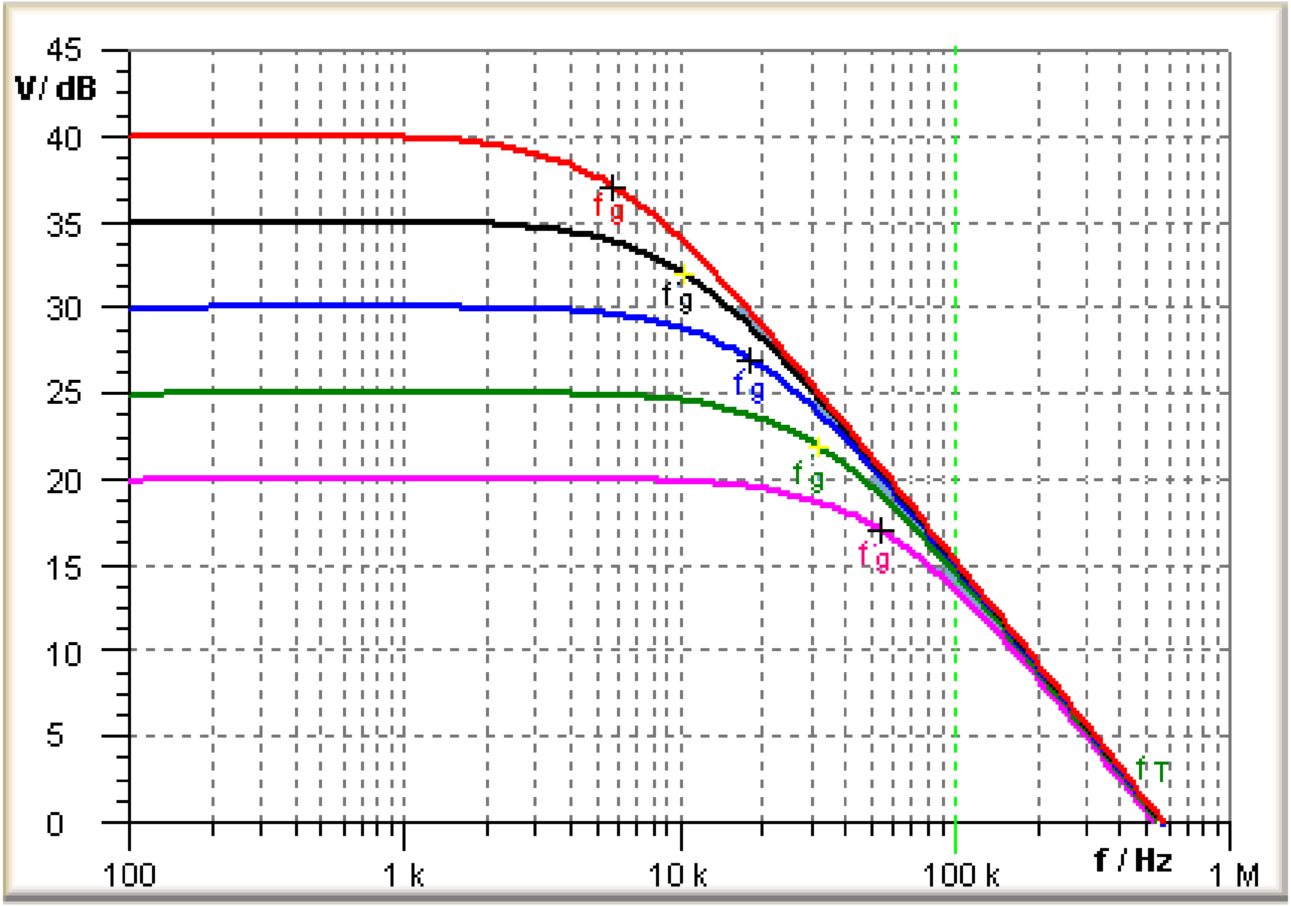
[2] **Transition Frequency**

The transition frequency is the frequency at which the gain has fallen to 1 (0 dB). This is an absolute limit of the OP operated as an amplifier. The transition frequency is also called the gain-bandwidth product. The transition frequency of the operational amplifier used here is approx. 500 kHz so that it cannot be measured with the COM3LAB instruments.

[3] **Remark on the Frequency Response**

The frequency response can only be recorded correctly if the system exhibits a linear behaviour, i.e. if the input signal is sinusoidal, the output signal must be sinusoidal too. If the output signal is not sinusoidal due to the influence of the slew rate (non-linear behaviour), the measurement is distorted. This occurs particularly at higher frequencies. It is also essential that the output amplitude does not become too great.

3.7 Result



The gain-bandwidth product of an operational amplifier is constant and equal to the transition frequency[1] .

This means that a greater d.c. gain can only be achieved with a smaller cutoff frequency.

We have:

$V_0 f_g \approx f_T = \text{const}$

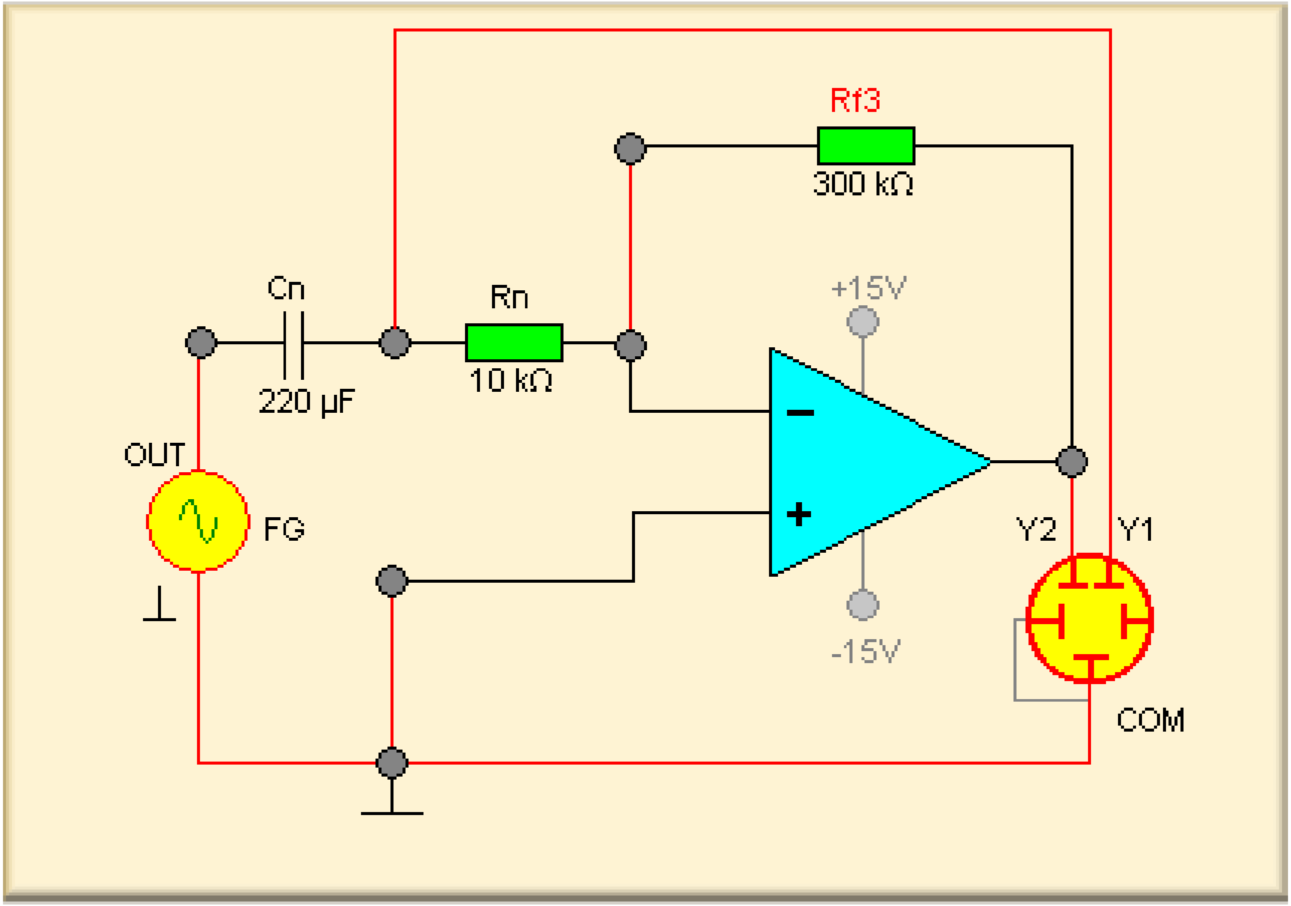
Example:
With $f_T = 550$ kHz it follows that

f_g (V_0=100) = 5.5 kHz
f_g (V_0=30) = 18.3 kHz

[1] **Transition Frequency**

The transition frequency is the frequency at which the gain has fallen to 1 (0 dB). This is an absolute limit of the OP operated as an amplifier. The transition frequency is also called the gain-bandwidth product. The transition frequency of the operational amplifier used here is approx. 500 kHz so that it cannot be measured with the COM3LAB instruments.

3.8 Override

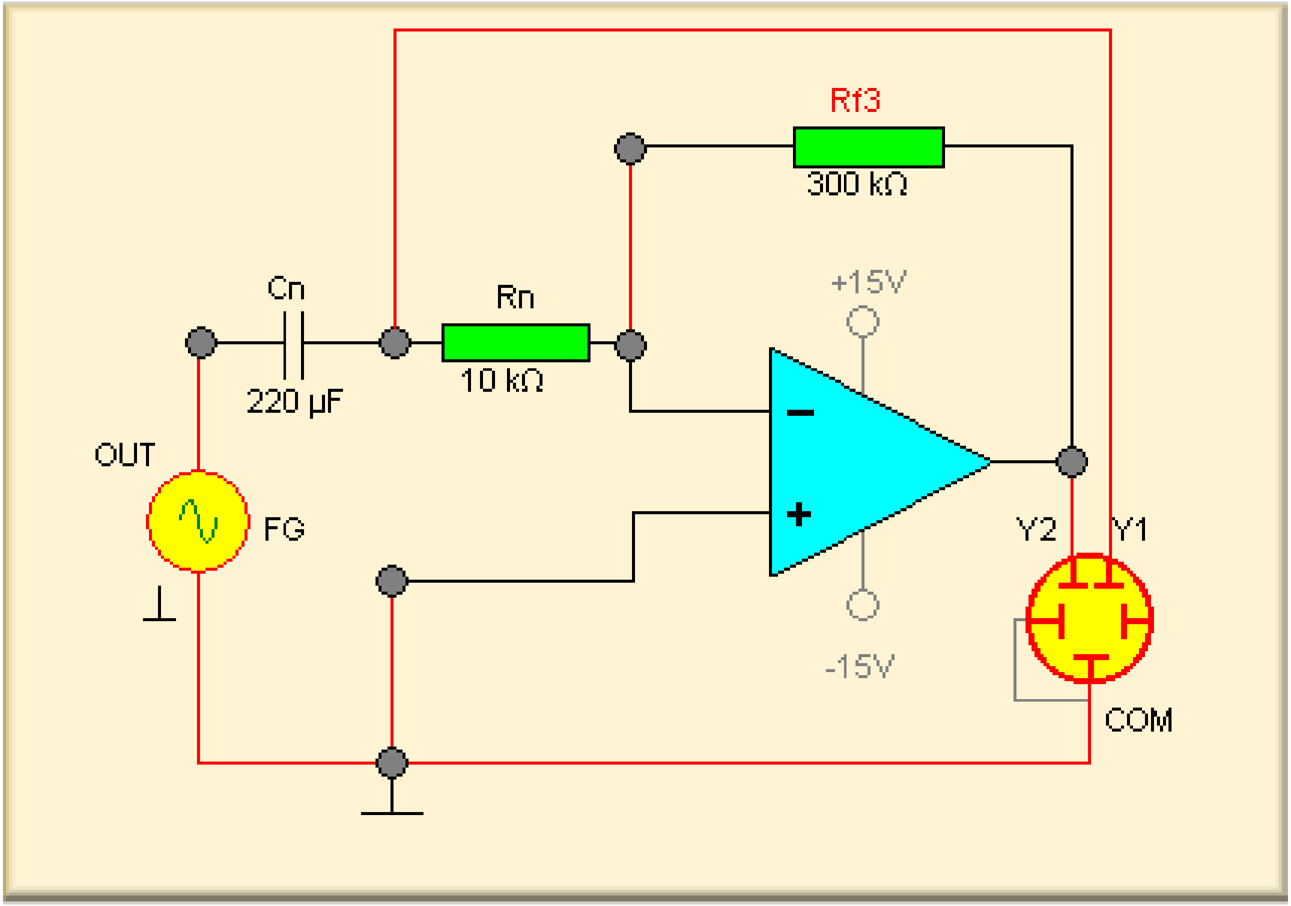


In theory, the output voltage would exceed the supply voltage in case of too great a gain or too high an input voltage. Therefore the operational amplifier cuts off the signal when it reaches the limits of the output range. The magnitude of these limits is about 1...3 V below the supply voltages. There are also OPAs with a so-called rail-to-rail[1] output range.

[1] **Rail-to-Rail**

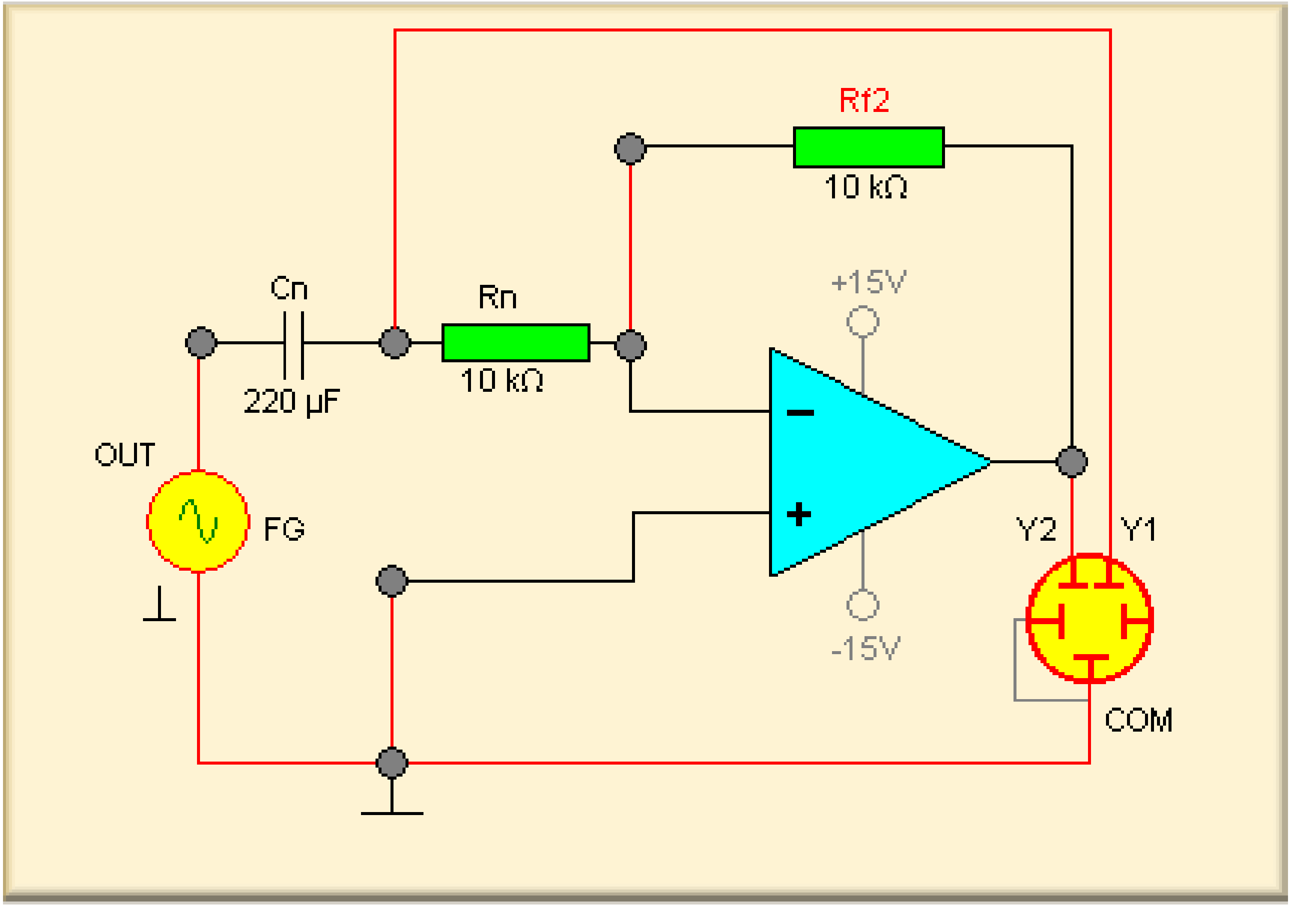
New generation OPAs in CMOS technology for a lower operating voltage (3 .. 5 V) make it possible to modulate the output within the whole range of the supply voltage.

3.9 Phase angle



The input and output voltages of an inverting amplifier have exactly opposite signs (for d.c. and low frequencies). Thus there is a phase shift of 180° between the output and the input signal.

3.10 Phase-frequency response

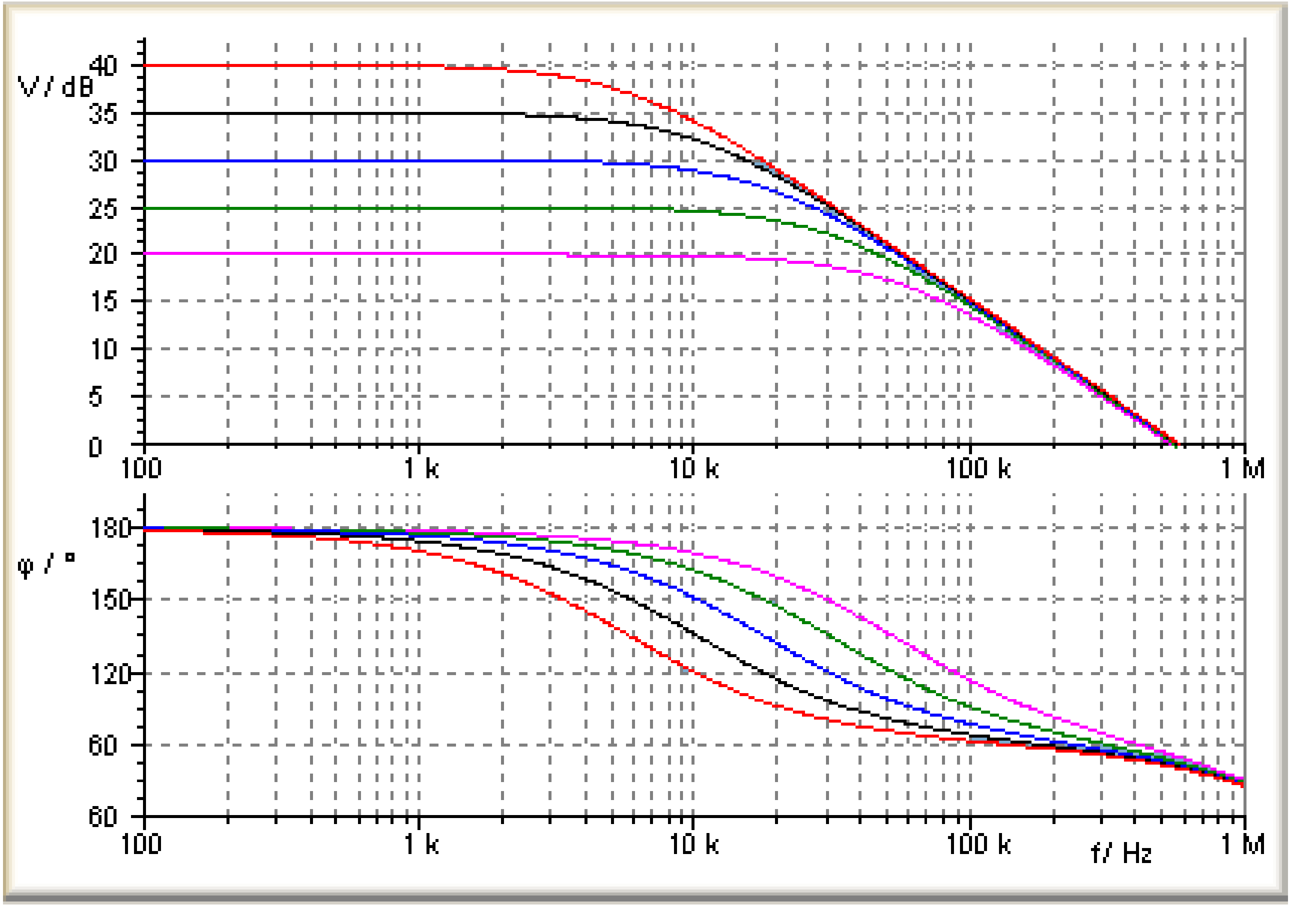


The internal capacitances and the switching times of the transistors integrated in the operational amplifier cause a change to the phase shift between the input and the output signal as the frequency increases. Please read the additional information on measuring the phase response[1] .

[1] **Measuring the Phase Response**

The phase response is measured by determining the time difference between the zero crossing of the input signal and the zero crossing of the output signal. The phase shift can be calculated together with the frequency information. Metrologically, the definition of the phase shift is only meaningful in the ranges from 0 to 360° or –180° to +180° respectively.

3.11 Result

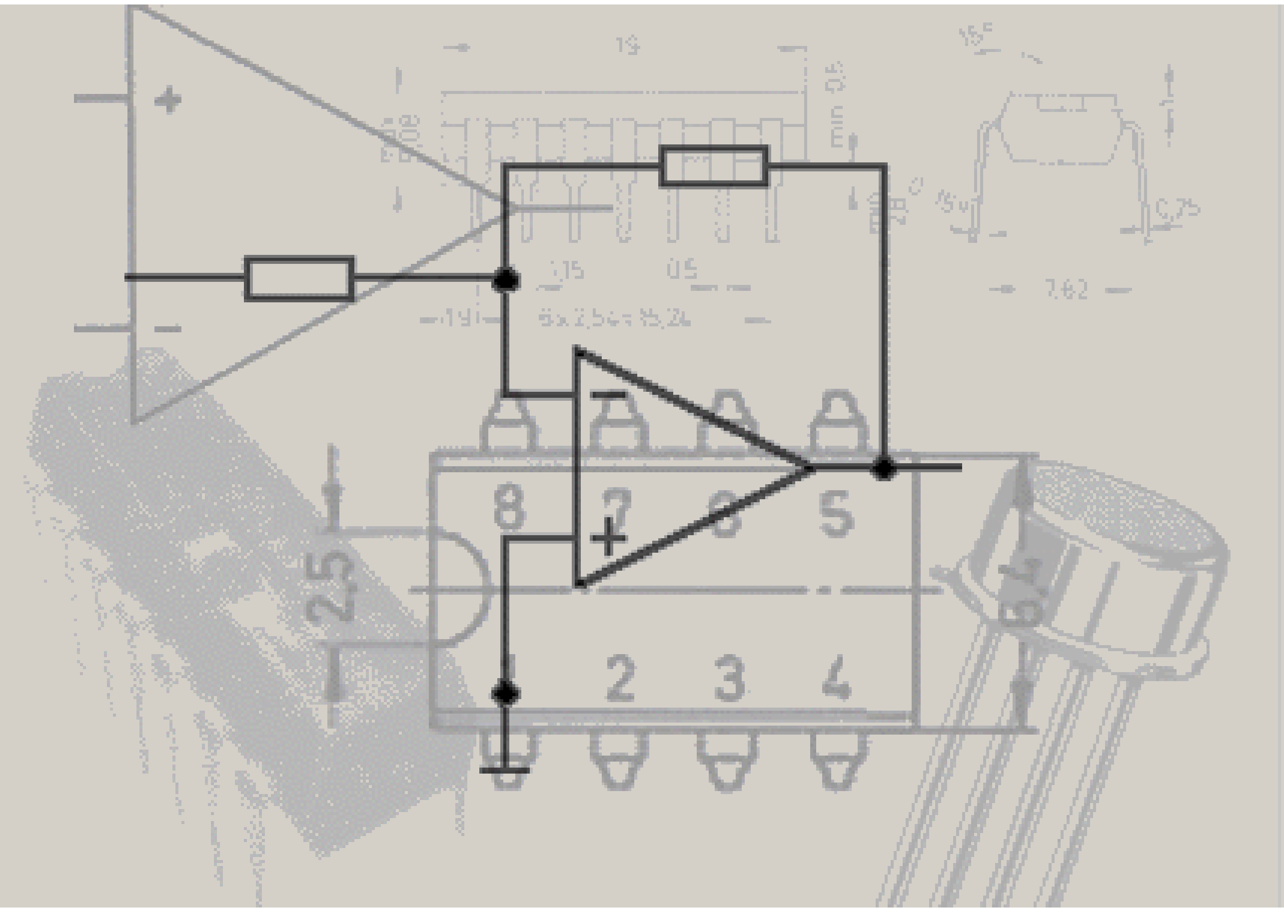


The phase shift changes with increasing frequency.

This effect is more pronounced if the gain (given by R_f) is great.

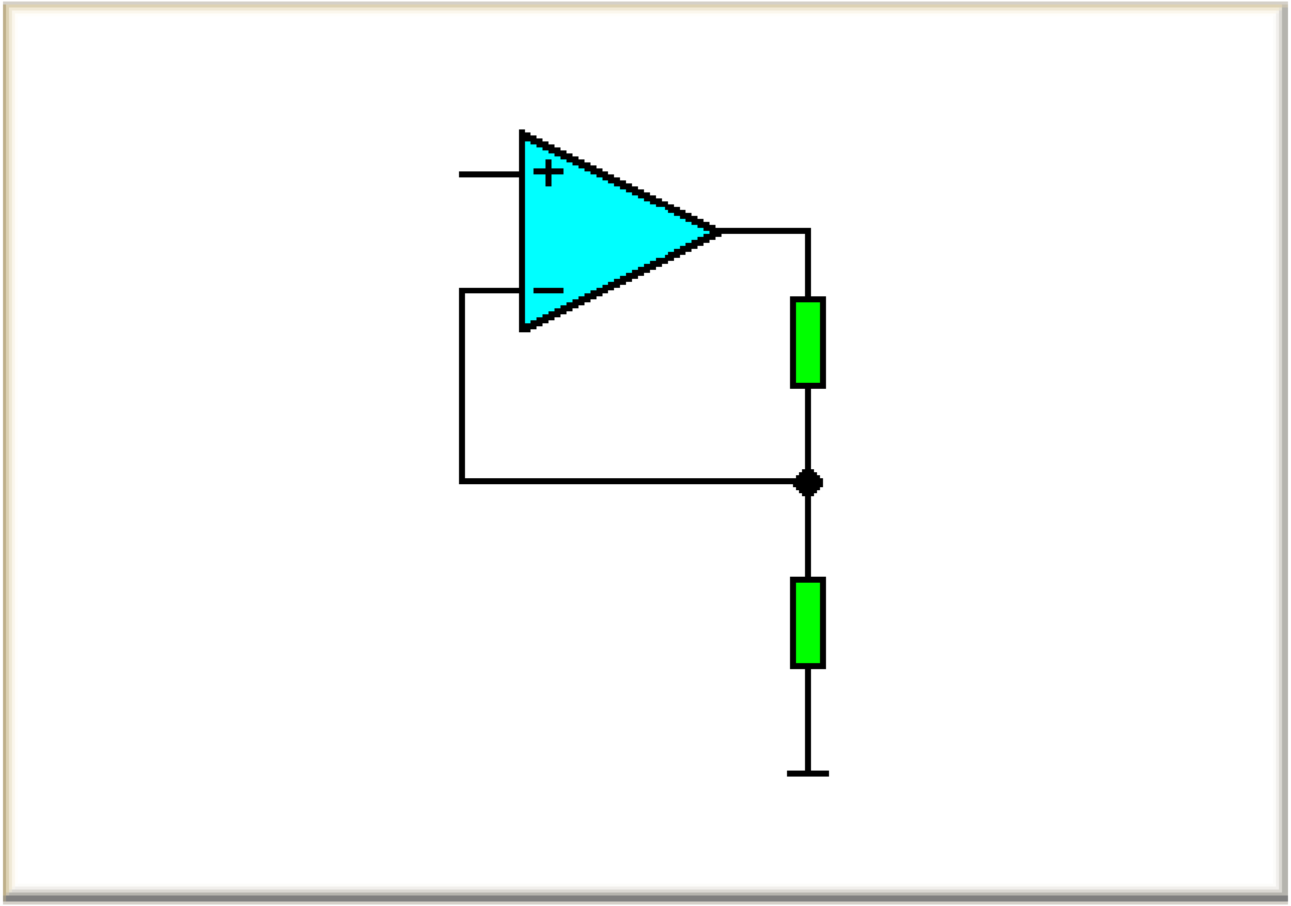
Regarding the amplitude-frequency response that means that the decrease in gain is accompanied by a change in the phase shift when the frequency increases.

3.12 Application



The inverting amplifier is used in communications, measuring and control engineering. Moreover, it is the basis of many applications, some of which are described in the following chapters, e.g. integrators, differentiators and active filter circuits.

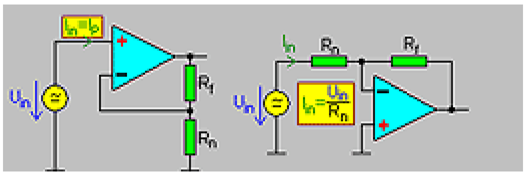
4.1 Introduction



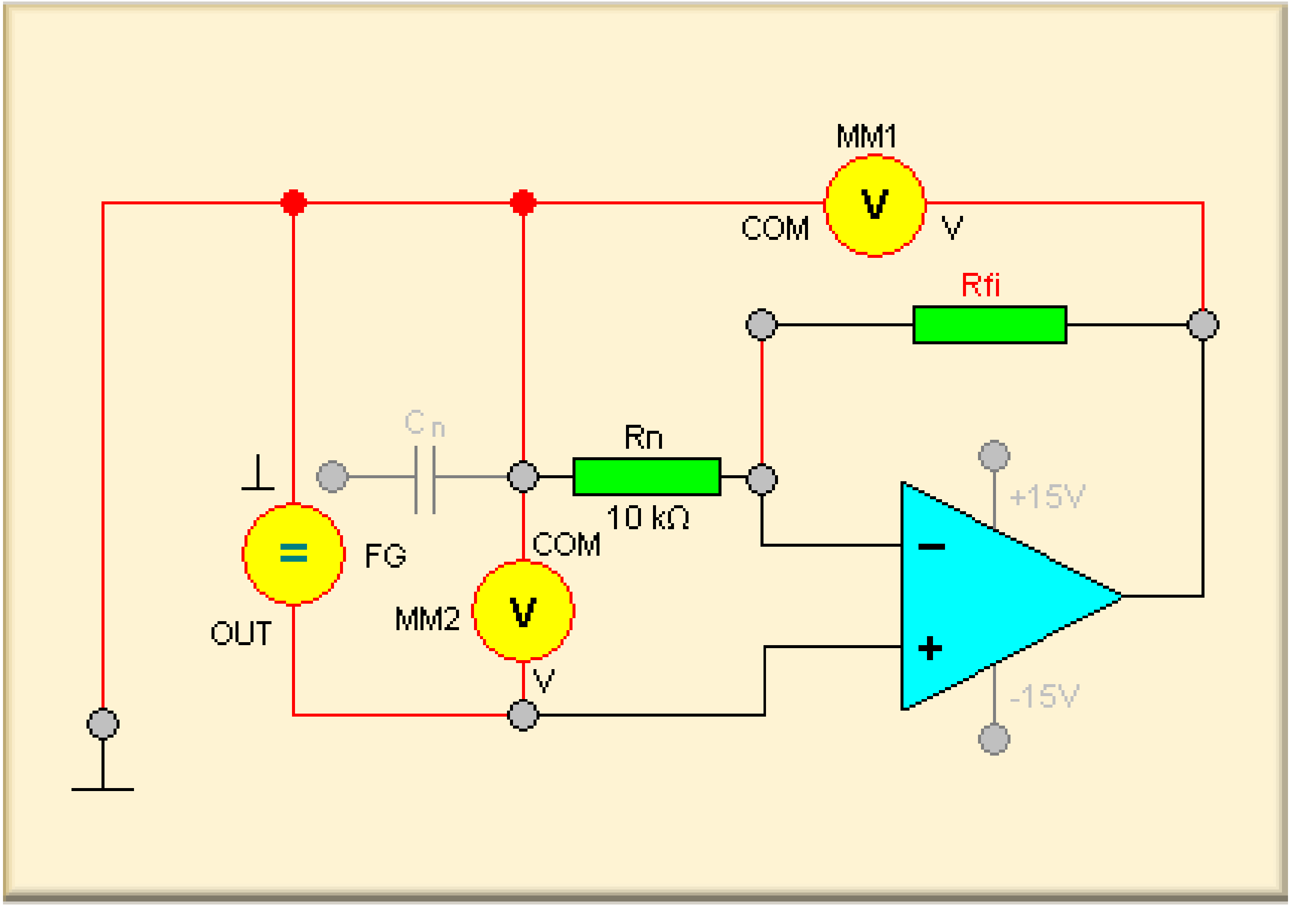
In the case of a non-inverting operational amplifier the signal to be amplified is fed into the non-inverting input. Therefore the signs of the output voltage and the input voltage are equal. However, the feedback takes place via the inverting input as in the case of the inverting amplifier. The input signal is loaded with a very small positive input current. So the control is powerless[1] .

[1] **Powerless**

At a non-inverting amplifier, the input signal source is only loaded with the positive input current (in the nA range). At an inverting amplifier, the load of the input signal source depends on its voltage and the resistance R_n.



4.2 Formula for the voltage gain



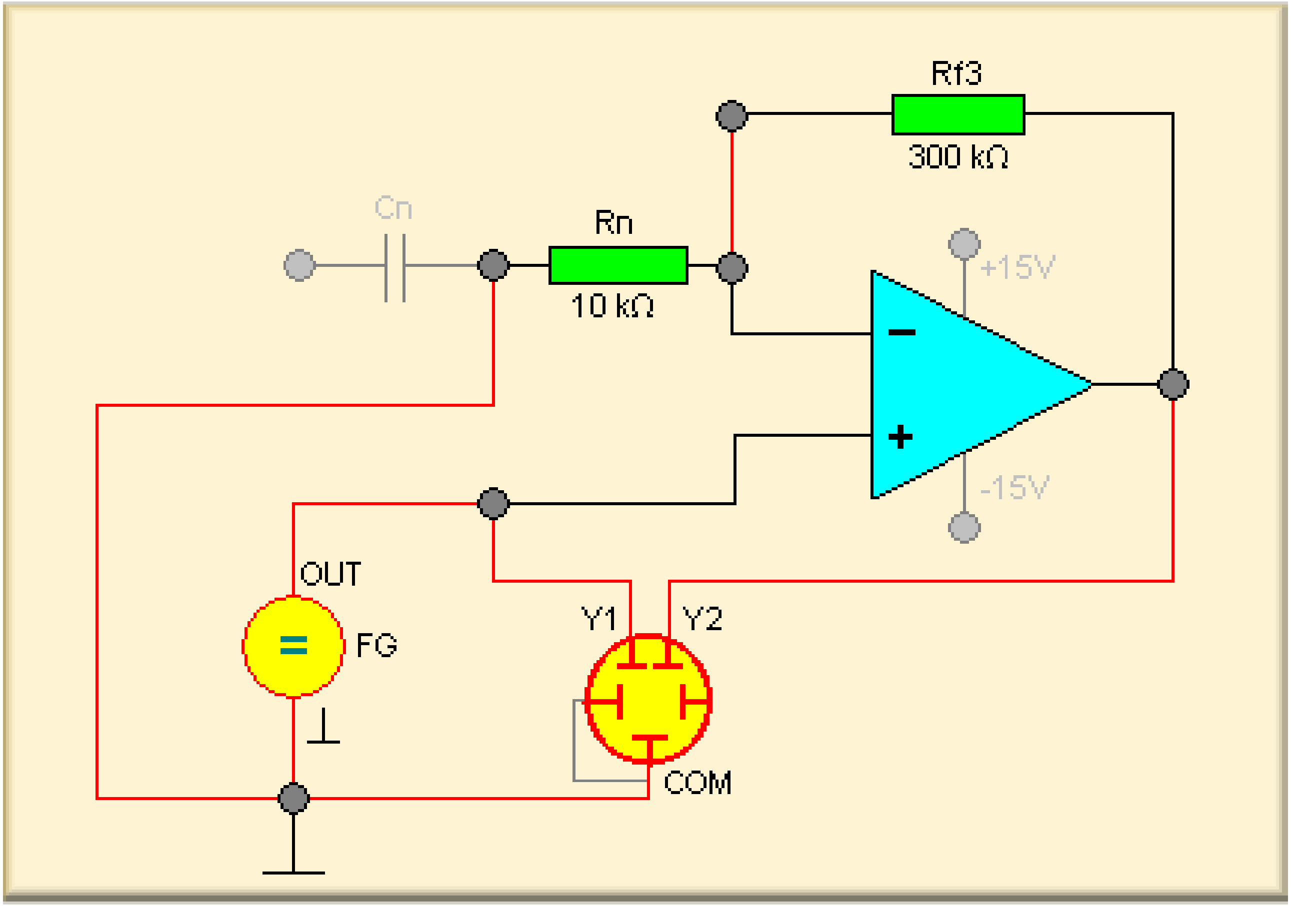
Because of the very small difference voltage between the two inputs, the inputs are approximately on the same potential. That means the voltage drop at R_n corresponds to the input voltage and the voltage drop at R_n and R_{fi} corresponds to the output voltage. Here R_n and R_{fi} form a voltage divider. The gain therefore is:

$$V_u = \frac{U_{R_n} + R_{R_{f1}}}{U_{R_n}} = 1 + \frac{R_{fi}}{R_n}$$

with

$R_n =$ 10 kΩ
$R_{fi} =$ (5.1 kΩ; 10 kΩ; 300 kΩ; 1 MΩ)

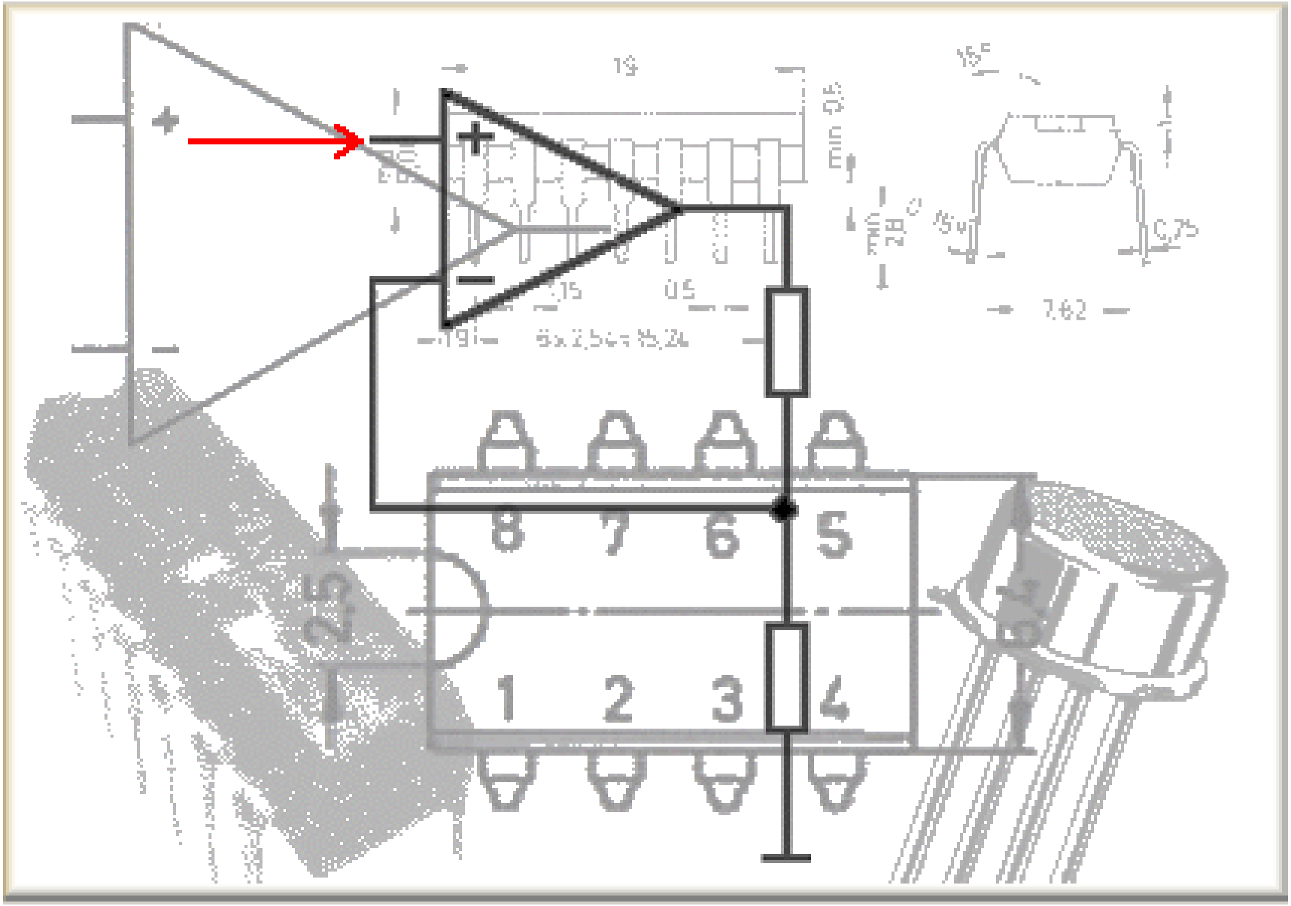
4.3 Phase angle



The output voltage and input voltage at a non-inverting amplifier have equal signs (for d.c. and low frequencies). So the a.c. signal at the output is in phase with the input signal.

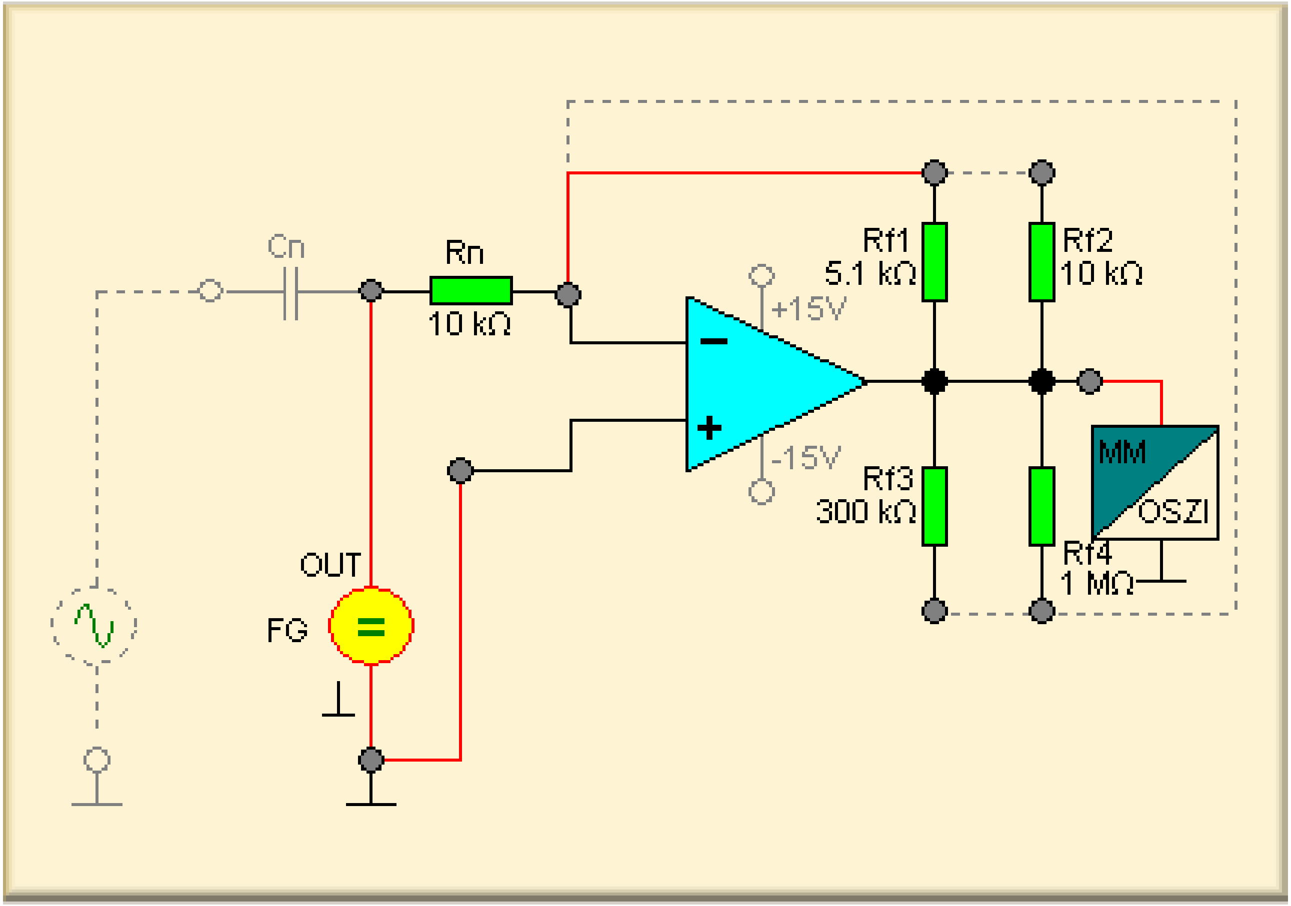
The phase response is comparable with that of an inverting OPA apart from the fact that the latter starts from 180° instead of 0°.

4.4 Application



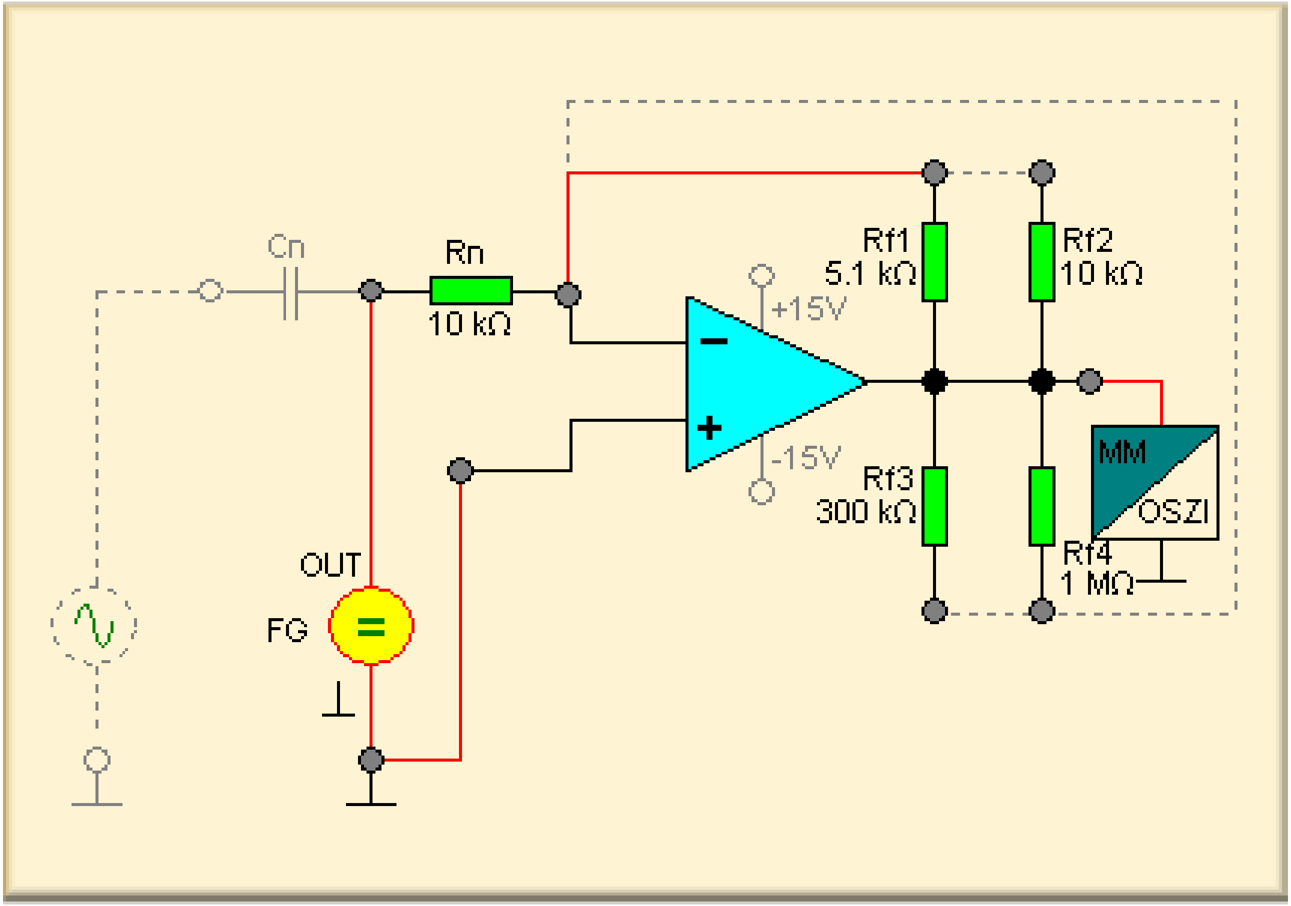
Like the non-inverting amplifier, the inverting amplifier is used in communications, measuring and control engineering. The inverting amplifier, too, is the basis of many applications, some of which are described in the following chapters. It is employed when a phase shift between the input and output in undesirable or when the signal to be amplified should not be loaded.

5.1 Introduction



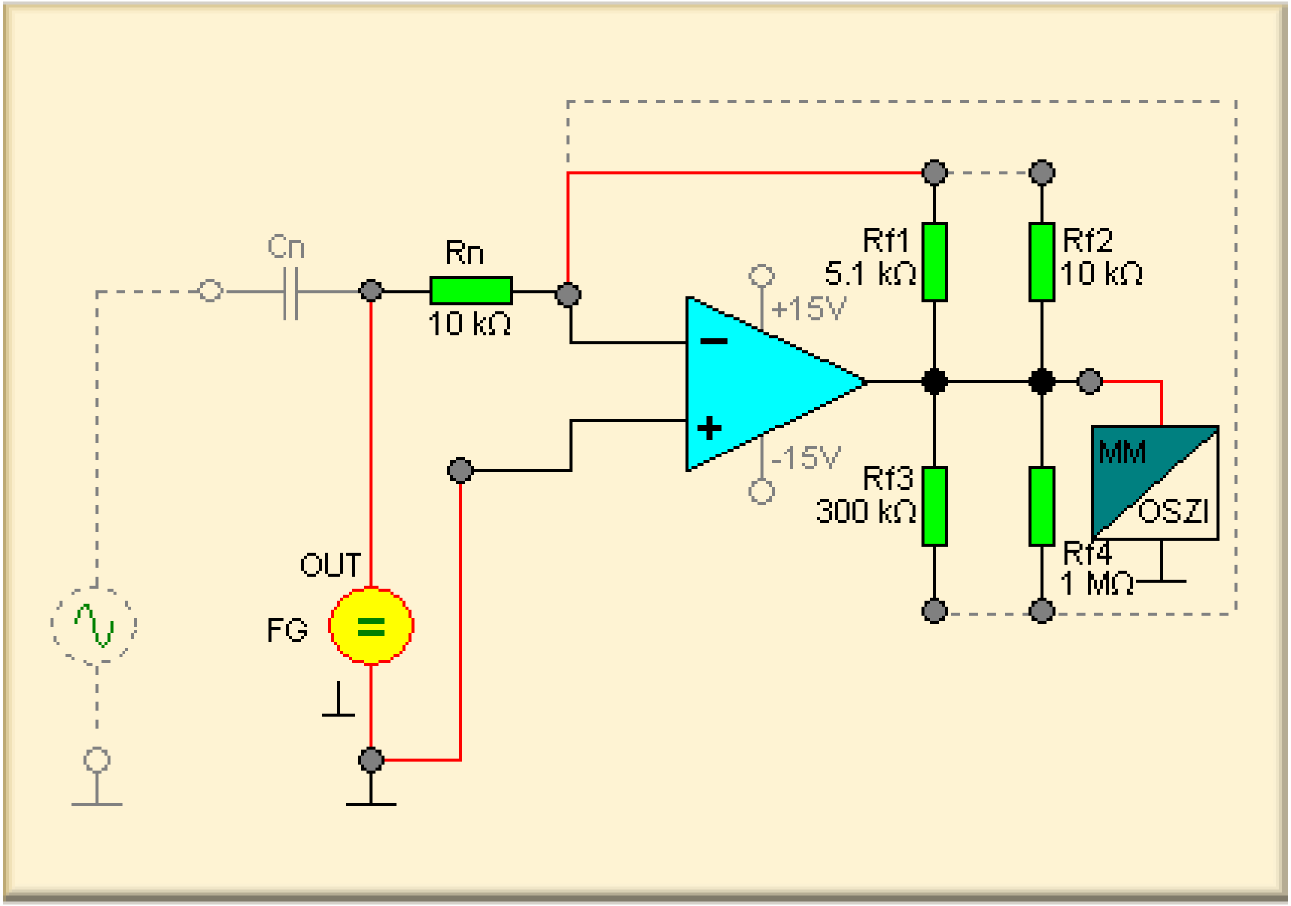
This chapter deals with finding faults in circuits and with correctly inferring types of faults from measured values. In each of the following four experiments one fault is activated. Here a fault means an obvious deviation of the circuit from the behaviour of the circuit as required by theory (see the previous chapters). Your task will be to determine the fault by making suitable measurements.

5.2 Fault No. 1



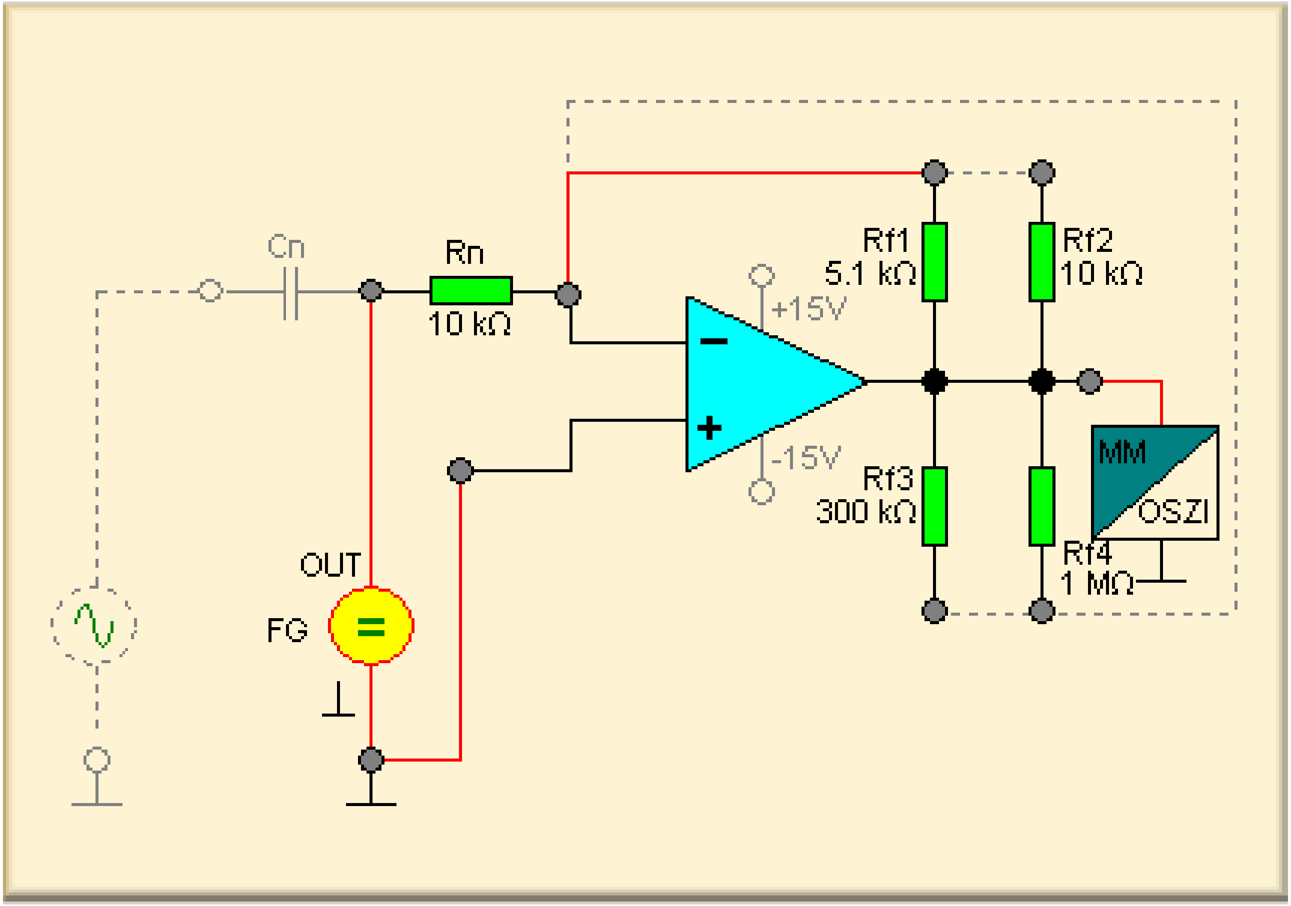
Now the first type of fault has been activated. Check **all** kinds of circuits of the inverting amplifier one after another and try to track down the fault. Use the multimeters or the oscilloscope for your measurements. Vary the input signal (supply d.c. after C_n, a.c. before C_n).

5.3 Fault No. 2



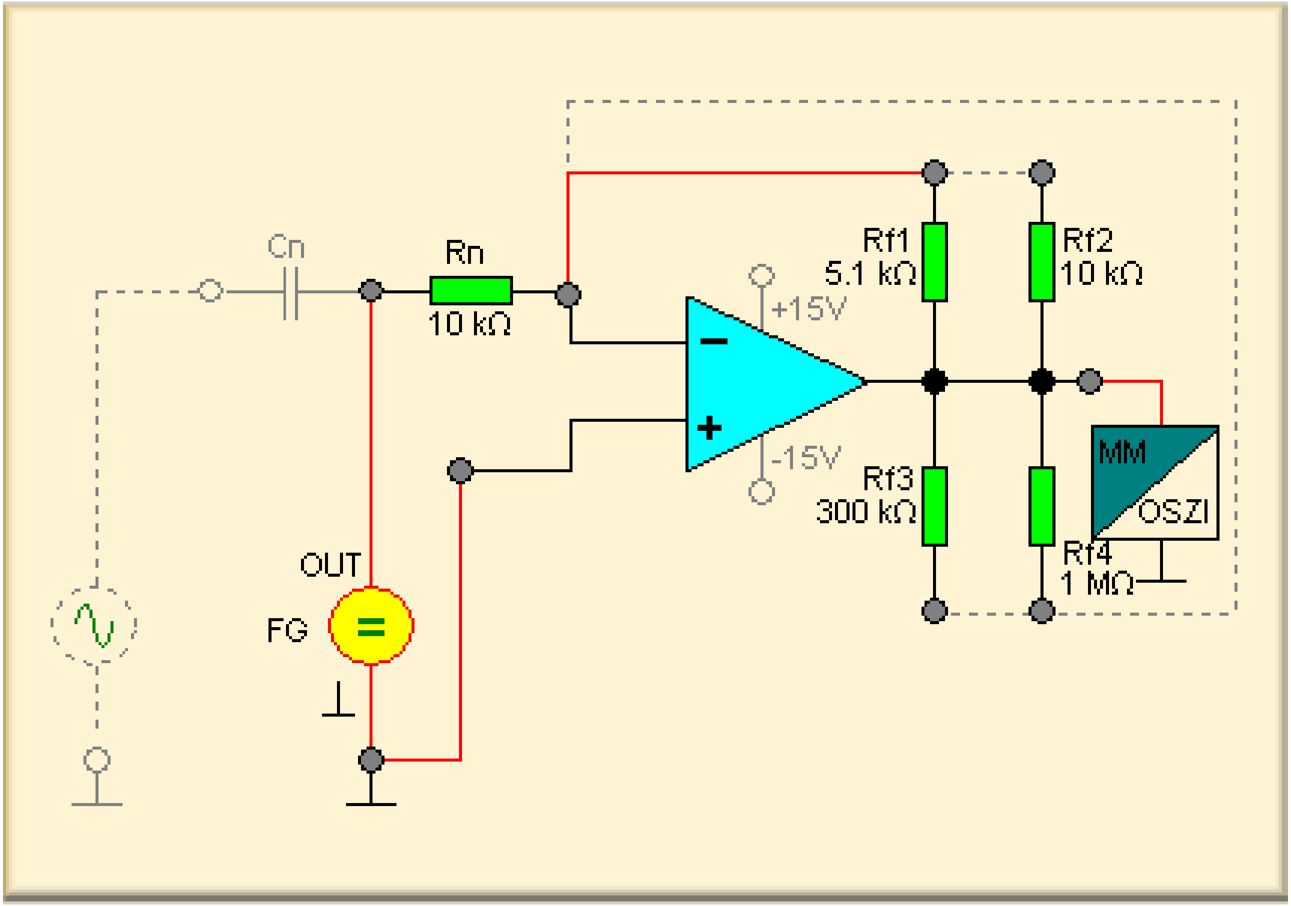
Now another type of fault has been activated. Check **all** kinds of circuits of the inverting amplifier one after another and try to track down the fault. Use the multimeters or the oscilloscope for your measurements. Vary the input signal (supply d.c. after C_n, a.c. before C_n).

5.4 Fault No. 3



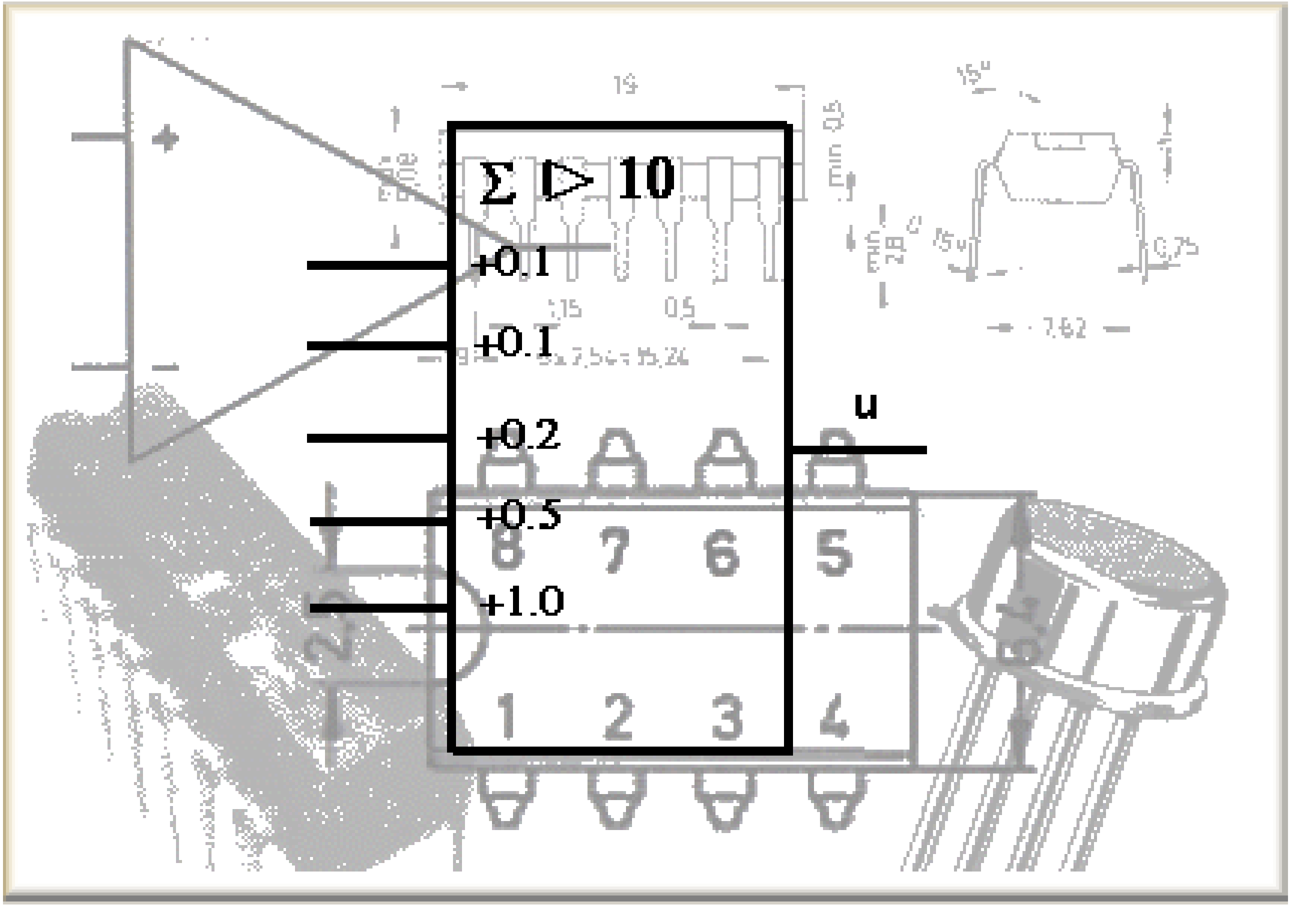
Now another type of fault has been activated. Check **all** kinds of circuits of the inverting amplifier one after another and try to track down the fault. Use the multimeters or the oscilloscope for your measurements. Vary the input signal (supply d.c. after C_n, a.c. before C_n).

5.5 Fault No. 4



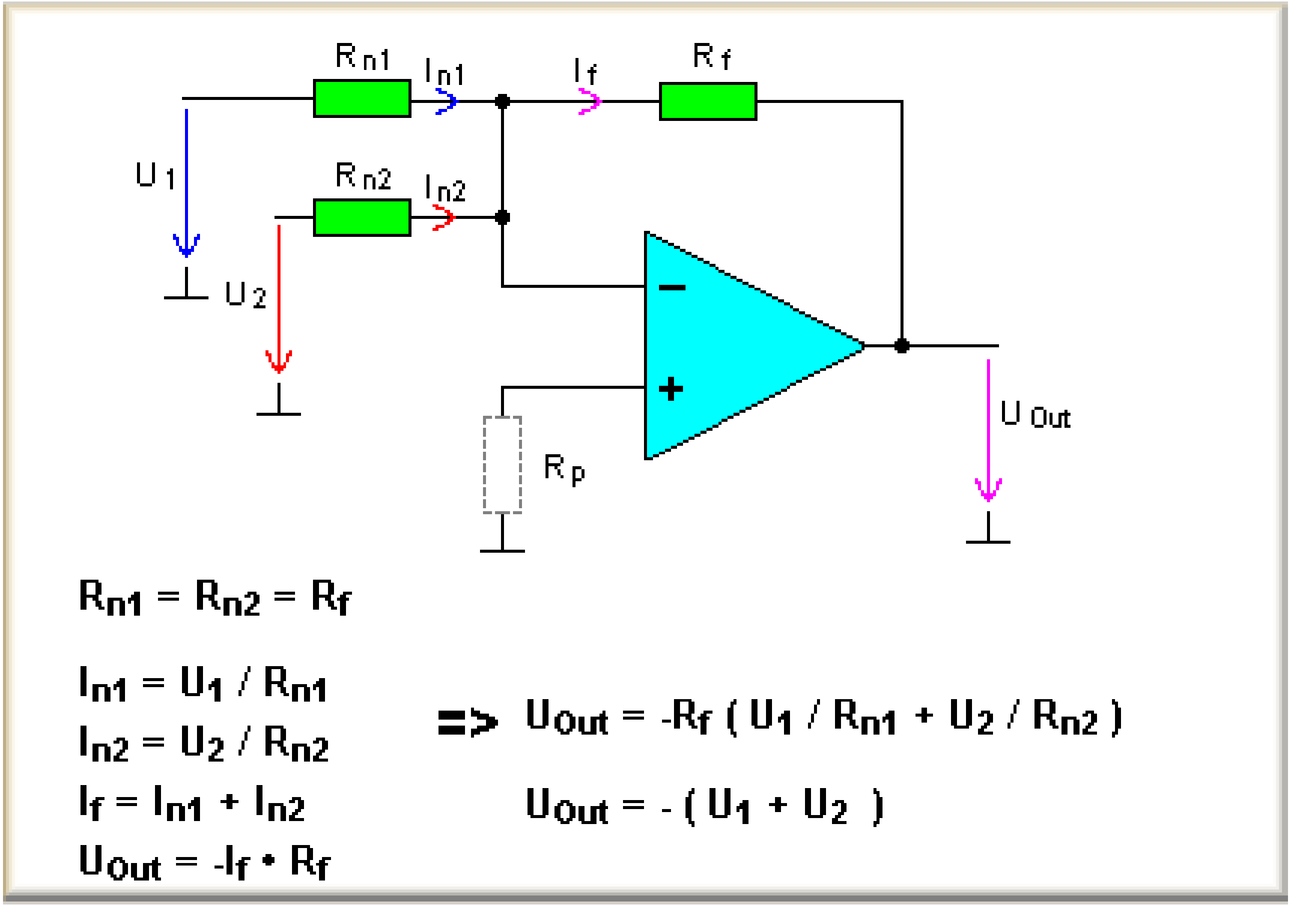
In this last experiment of this chapter another fault has been activated. Check **all** kinds of circuits of the inverting amplifier one after another and try to track down the fault. Use the multimeters or the oscilloscope for your measurements. Vary the input signal (supply d.c. after C_n, a.c. before C_n).

6.1 Introduction



It is easy to extend the inverting amplifier so that it forms a summer. Several input resistances of equal magnitude allow an arbitrary number of voltages to be added. The negative output voltage is then proportional to the sum of the input voltages.

6.2 Circuit setup



$$R_{n1} = R_{n2} = R_f$$

$$I_{n1} = U_1 / R_{n1}$$

$$I_{n2} = U_2 / R_{n2}$$

$$I_f = I_{n1} + I_{n2}$$

$$U_{Out} = -I_f \cdot R_f$$

$$\Rightarrow U_{Out} = -R_f \,(U_1 / R_{n1} + U_2 / R_{n2})$$

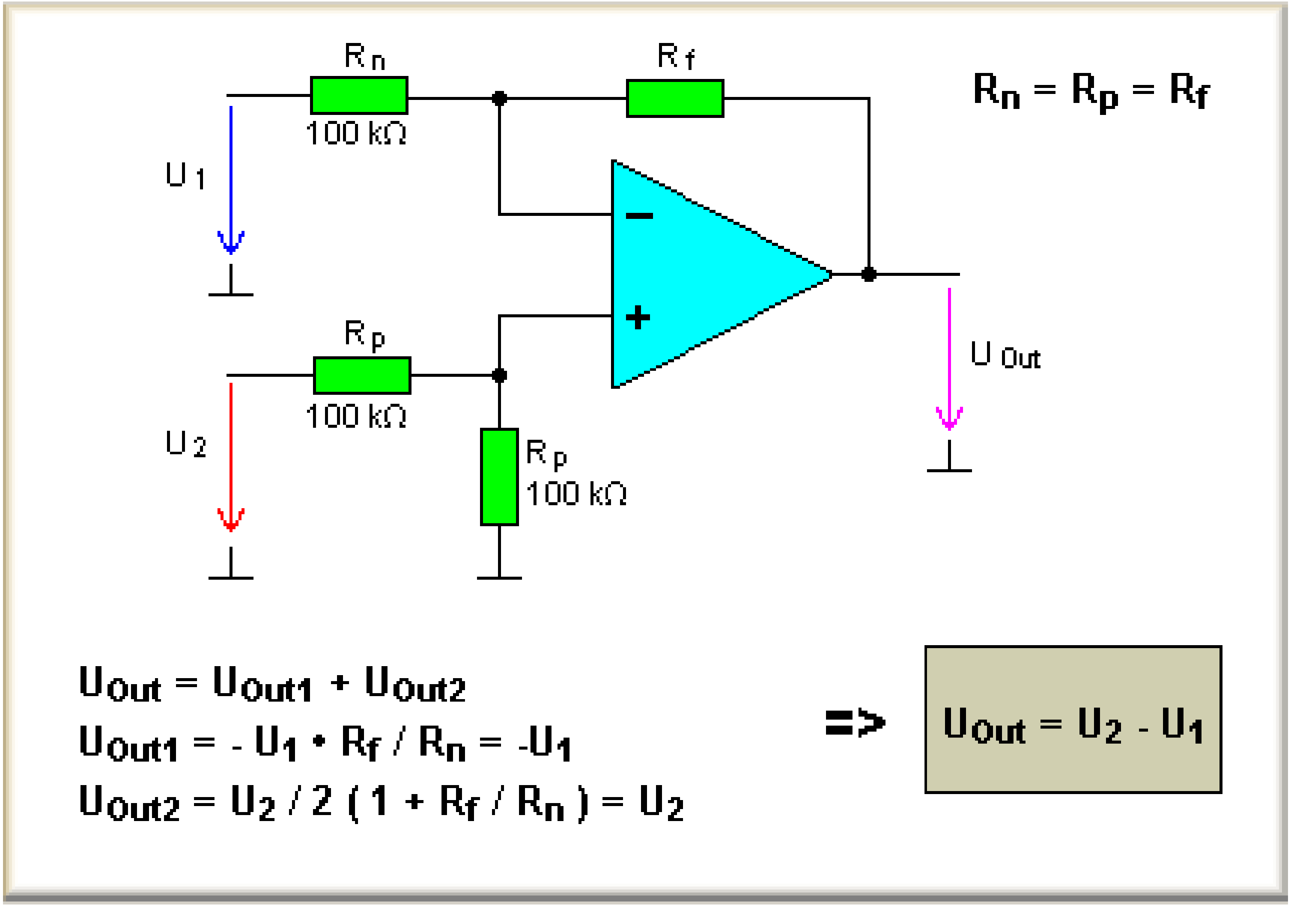
$$U_{Out} = - (U_1 + U_2)$$

The example shows how the addition of two voltages is realised. Because the inverting input is Virtually grounded (neglect of the voltage drop at R_P), the summer can be arbitrarily extended.

The voltages to be added are applied to the inverting input via the resistances R_{n1} and R_{n2}.

Remark:
The resistance R_p is present in this experiment field in order to allow a subtractor to be realised in the following experiments.

6.3 Subtractor



$$U_{Out} = U_{Out1} + U_{Out2}$$

$$U_{Out1} = - U_1 \cdot R_f / R_n = -U_1$$

$$U_{Out2} = U_2 / 2 \, (1 + R_f / R_n) = U_2$$

$$\Rightarrow \boxed{U_{Out} = U_2 - U_1}$$

The signal to be subtracted is fed into the inverting input. This causes a difference voltage, to which the output voltage is proportional.

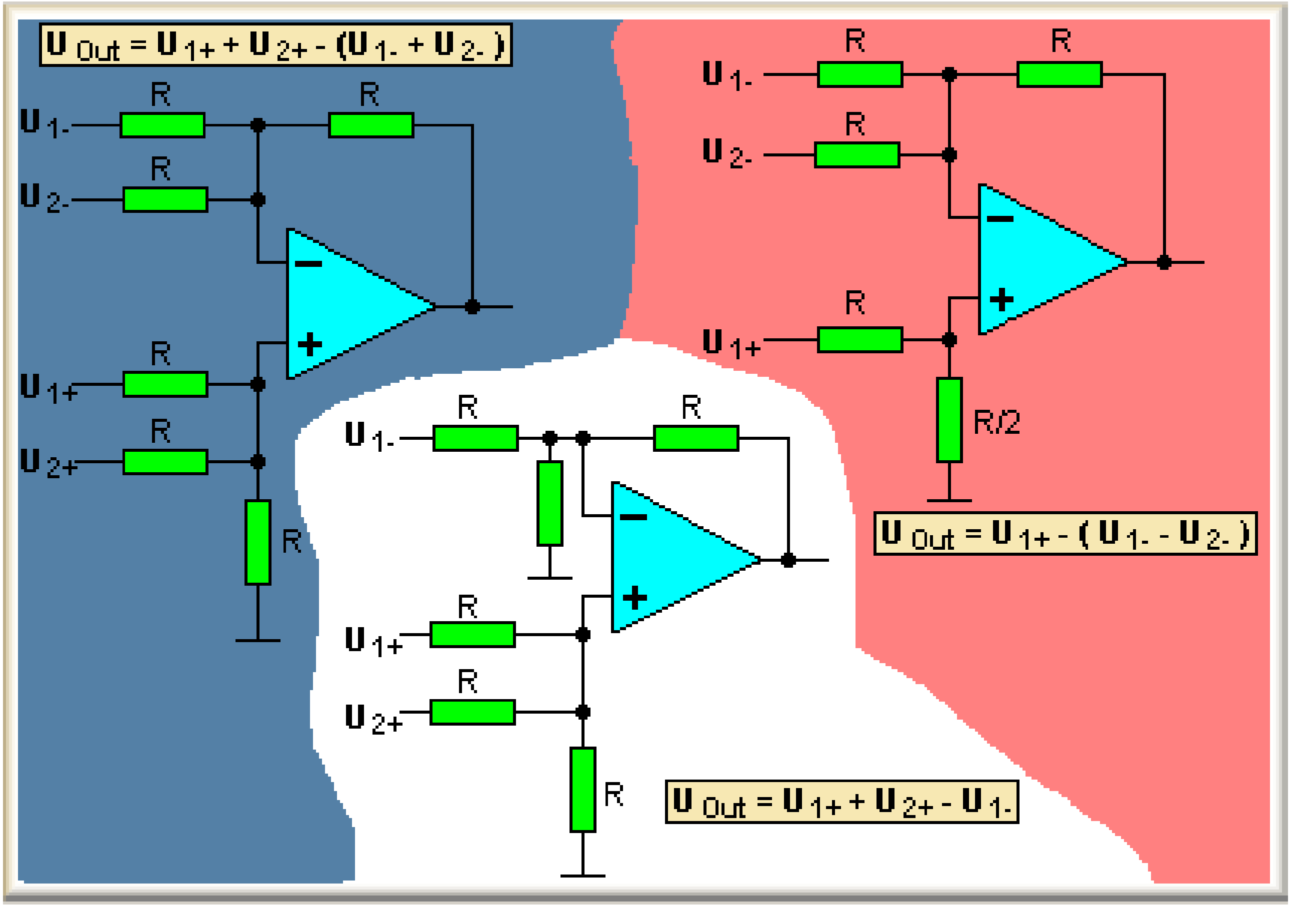
The output voltage can be calculated according to the principle of superposition[1] . For U_1 ($U_2 = 0$) the circuit behaves like an inverting amplifier with a gain of –**1**. For U_2 ($U_1 = 0$) the system is a non-inverting amplifier with an incoming voltage divider. The resulting gain is +**1** (the OPA has a gain of 2 and the voltage divider has a gain of 1/2).

---

[1] **Principle of Superposition**

According to the principle of superposition, the effect of a cause can be calculated independently from all other causes and effects in linear systems. The resulting effect is the sum of all individual effects.

6.4 Multiple subtractor



Like the adder, the subtractor can be extended.

In the case of a multiple subtractor, the addends are applied to the non-inverting input and the subtrahends to the inverting input.

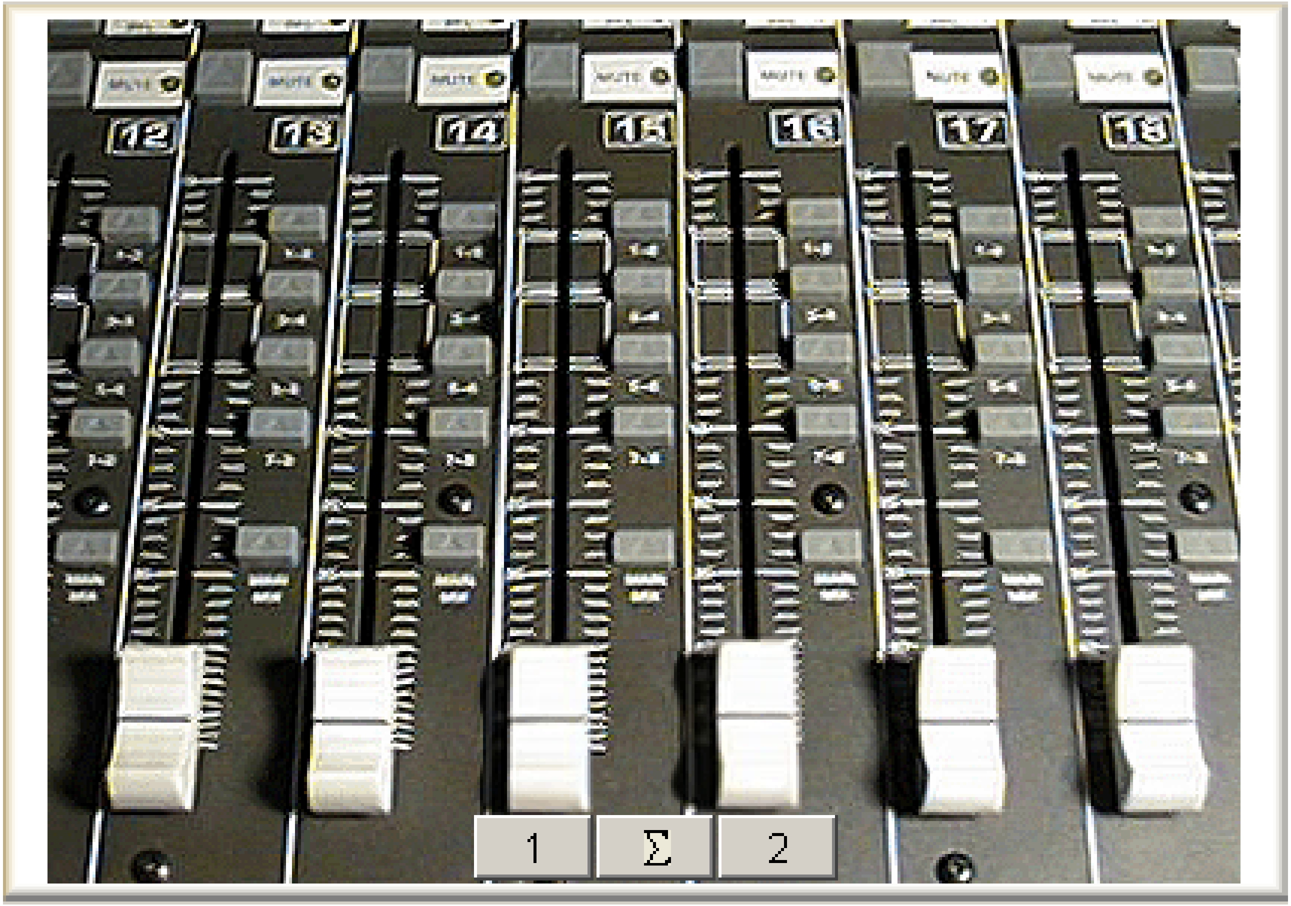
Here again the output voltage can be calculated according to the principle of superposition[1] .

---

[1] **Principle of Superposition**

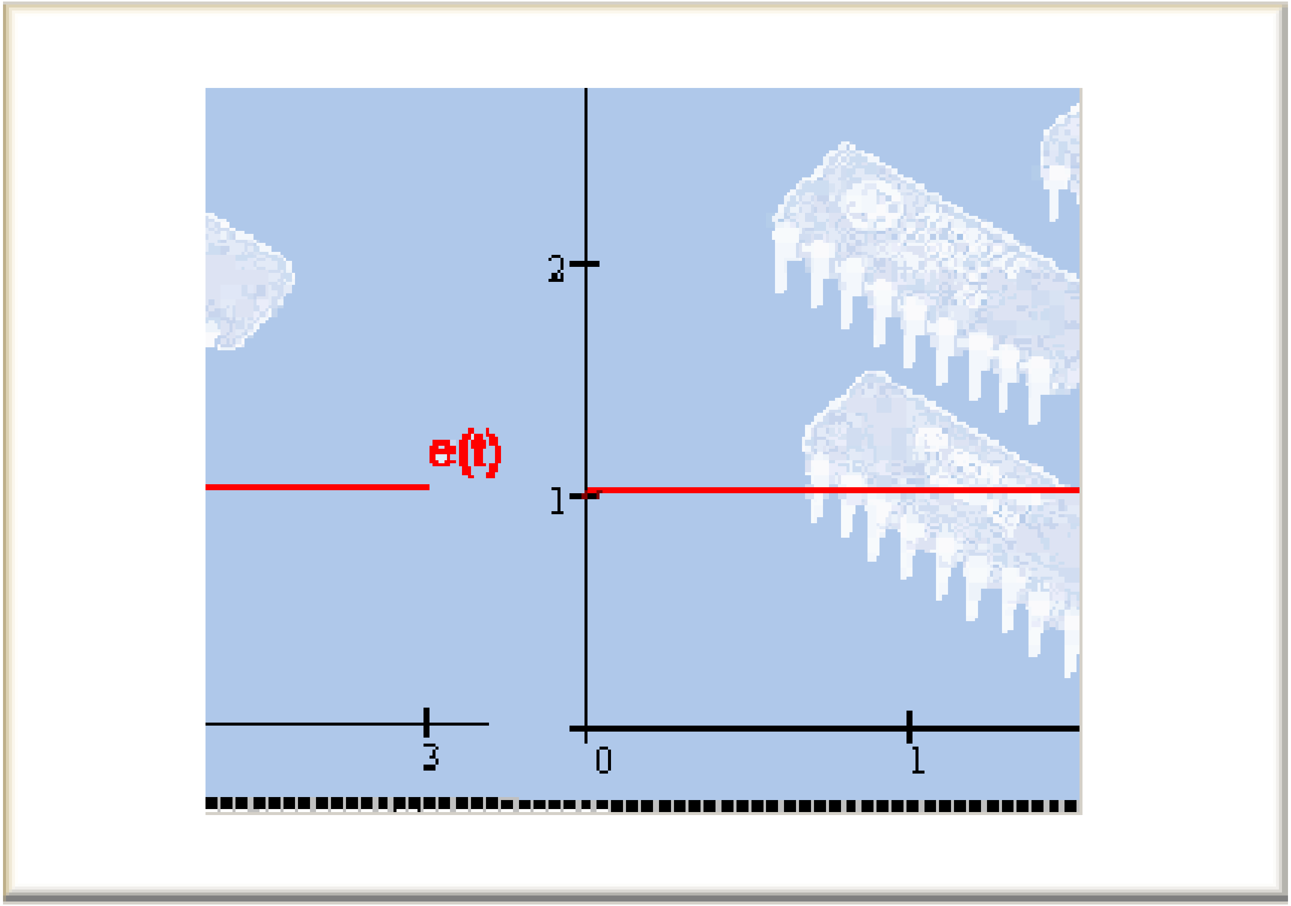
According to the principle of superposition, the effect of a cause can be calculated independently from all other causes and effects in linear systems. The resulting effect is the sum of all individual effects.

6.5 Supplementary information

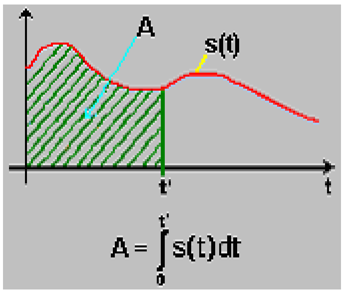


The adder and subtractor circuits just presented can also be used as a mixer. If, e.g., two different audio frequencies are applied to the inputs of an adder, these can be composed to form a complex sound.

7.1 Introduction



The output of an integrator is proportional to the integral[1] of a signal. The integral describes the area between the signal and the time axis.



$$A = \int_0^{t'} s(t)dt$$

Other integration examples[2] are found, e.g., in physics.

The basis of the integrator circuit is given by the inverting amplifier.

[1] **Integrator**

The output voltage of an integrator is a measure of the voltage-time area (area between the time axis and the voltage curve) of the input voltage.

[2] **Integration Examples**

In physics the following examples of integration are known.

1. The time integral of the velocity is the path length covered.

$$s = \int_0^t v(t)dt$$

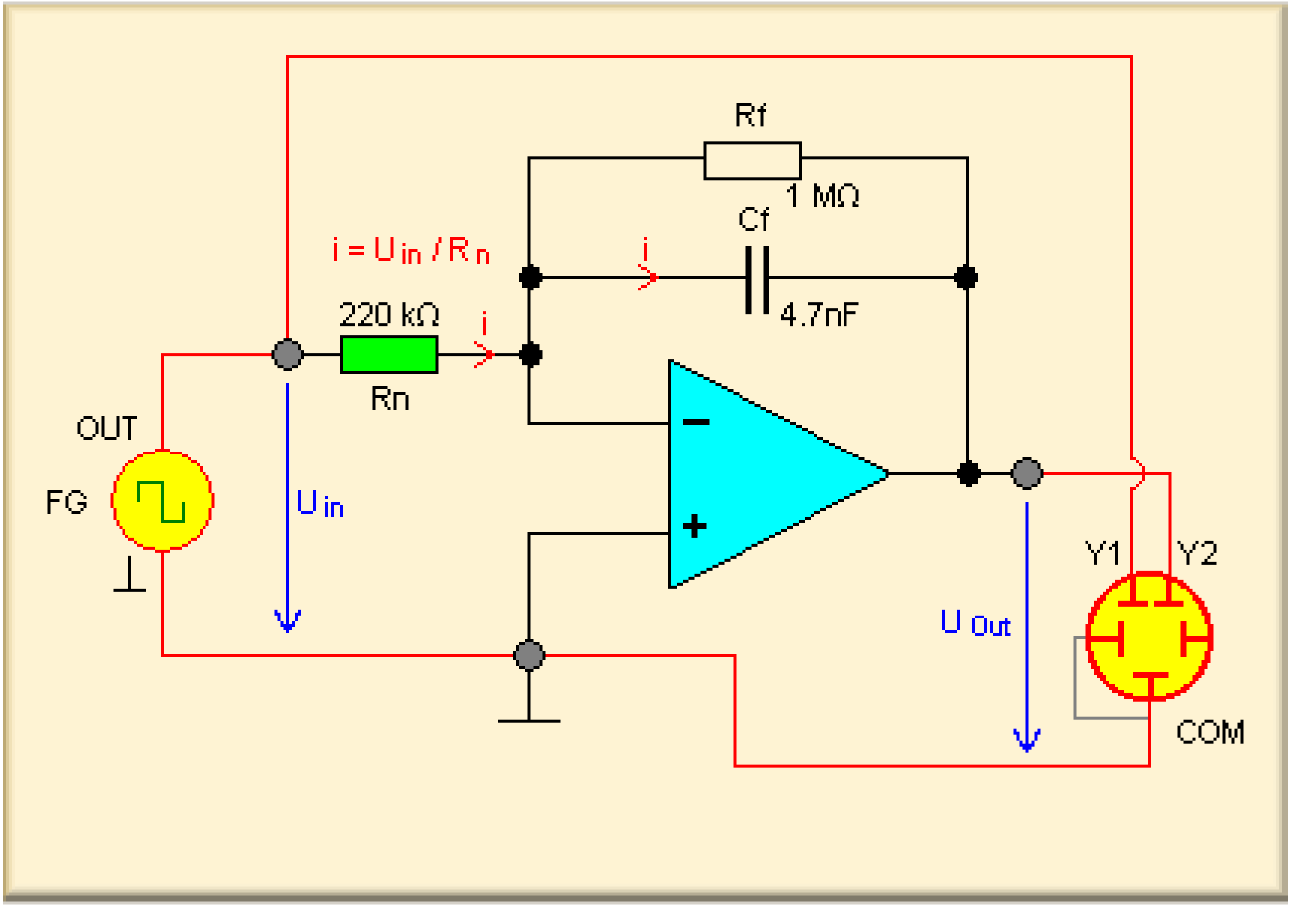
2 h at 50 km/h yields 100 km

2. The time integral of the power is the energy converted.

$$W = \int_0^t P(t)dt$$

1 kW during 2 h yields 2 kWh

7.2 Circuit setup

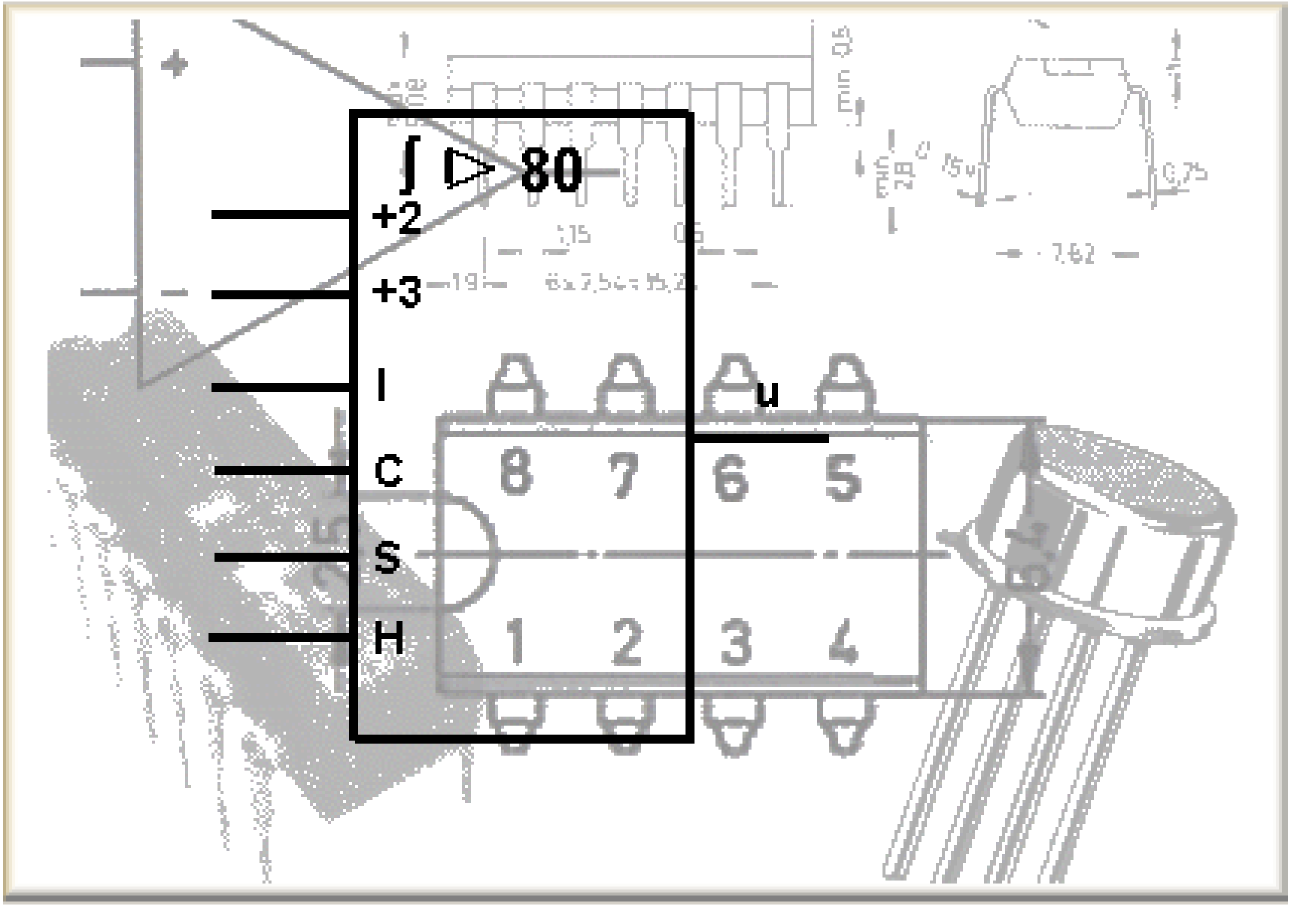


The output voltage is the charging voltage of the capacitor. The charging current is determined by R_n and by the input voltage. From this

$$U_{Out} = -\frac{1}{R_n \cdot C_f} \cdot \int U_{in}(t)dt$$

is obtained. The output signal is inverted relative to the actual course of the integral.

7.3 Result / application



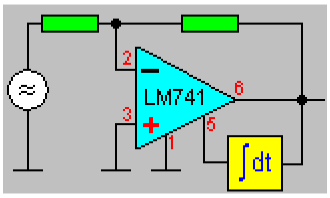
The integrator used to be employed in arithmetical circuits. Today it is of great importance in control engineering (integral-action controllers: I element[1]) and in designing function generators (signal shaping: rectangular to delta). Furthermore the integrator is employed, e.g., for the offset compensation in measuring amplifiers[2] .

[1] **I element**

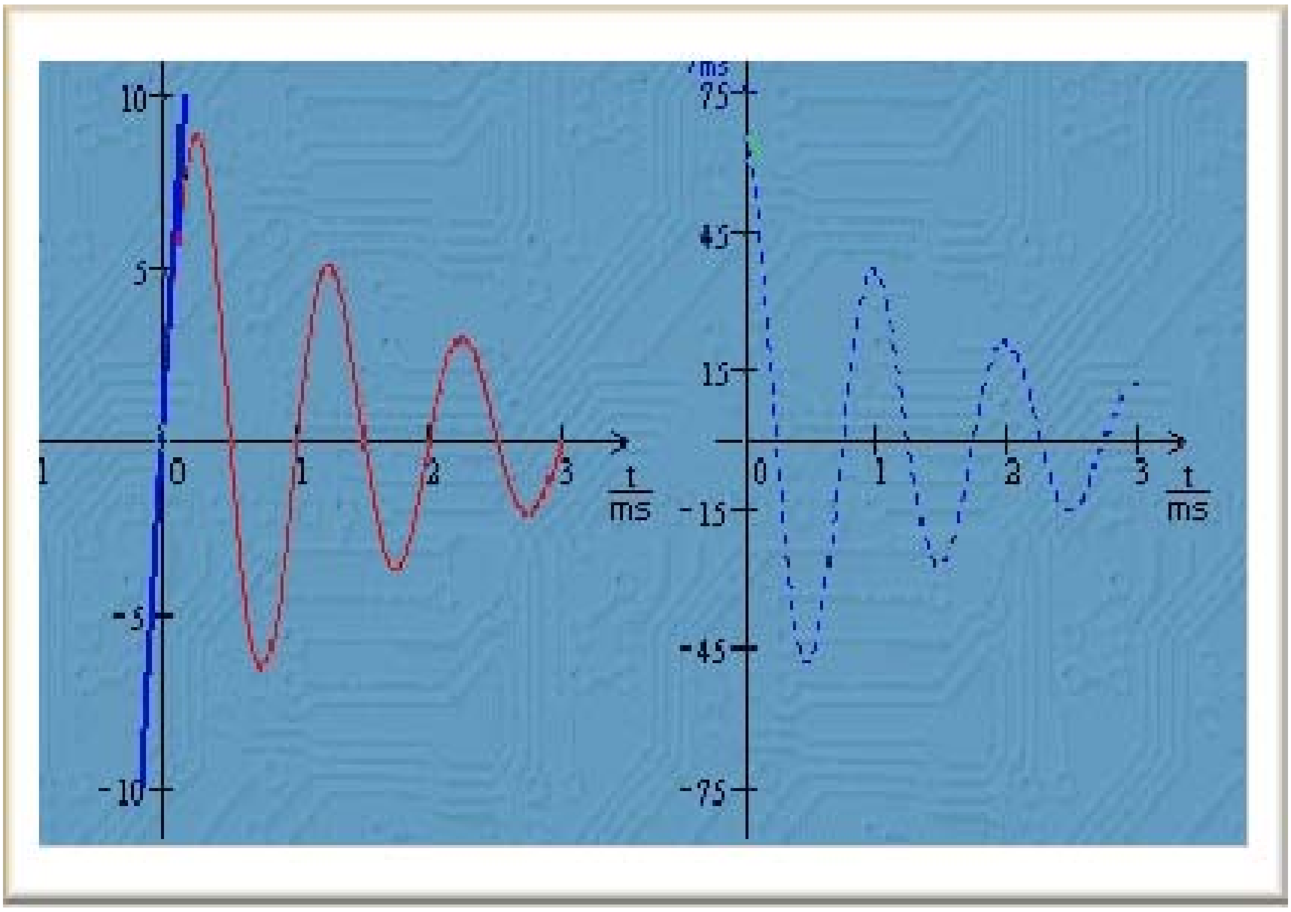
In control engineering, the I element provides a control variable which is proportional to the integral (time area) of the deviation. For details see Courses CT I (Cat.No. 700 82) and CT II (Cat.No. 700 83).

[2] **Offset Compensation in Measuring Amplifiers**

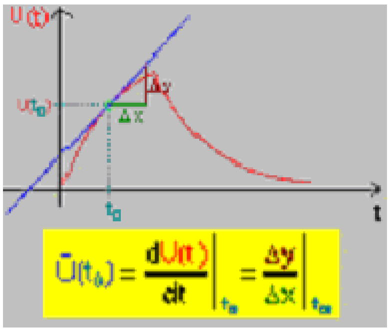
In order to eliminate the parasitic d.c. component at the output of a.c. amplifiers caused by the offset, an I-controller is set up with an integrator, which generates a signal as control variable for the offset compensation at the offset control inputs of the OPA. By this dynamic changes in the offset (e.g. due to temperature variation) are eliminated.



8.1 Introduction



The output of a differentiator is proportional to the time derivative of a signal, which describes the time rate of change of a signal. The value corresponds to the slope of the tangent at the curve at time t.



Other differentiation examples[1] are found, e.g., in physics.

The basis of a differentiation circuit is again given by the inverting amplifier.

[1] **Differentiation Examples**

From physics the following examples are known.

1. The time derivative of the path is the velocity.

$$v(t) = \frac{ds(t)}{dt}$$

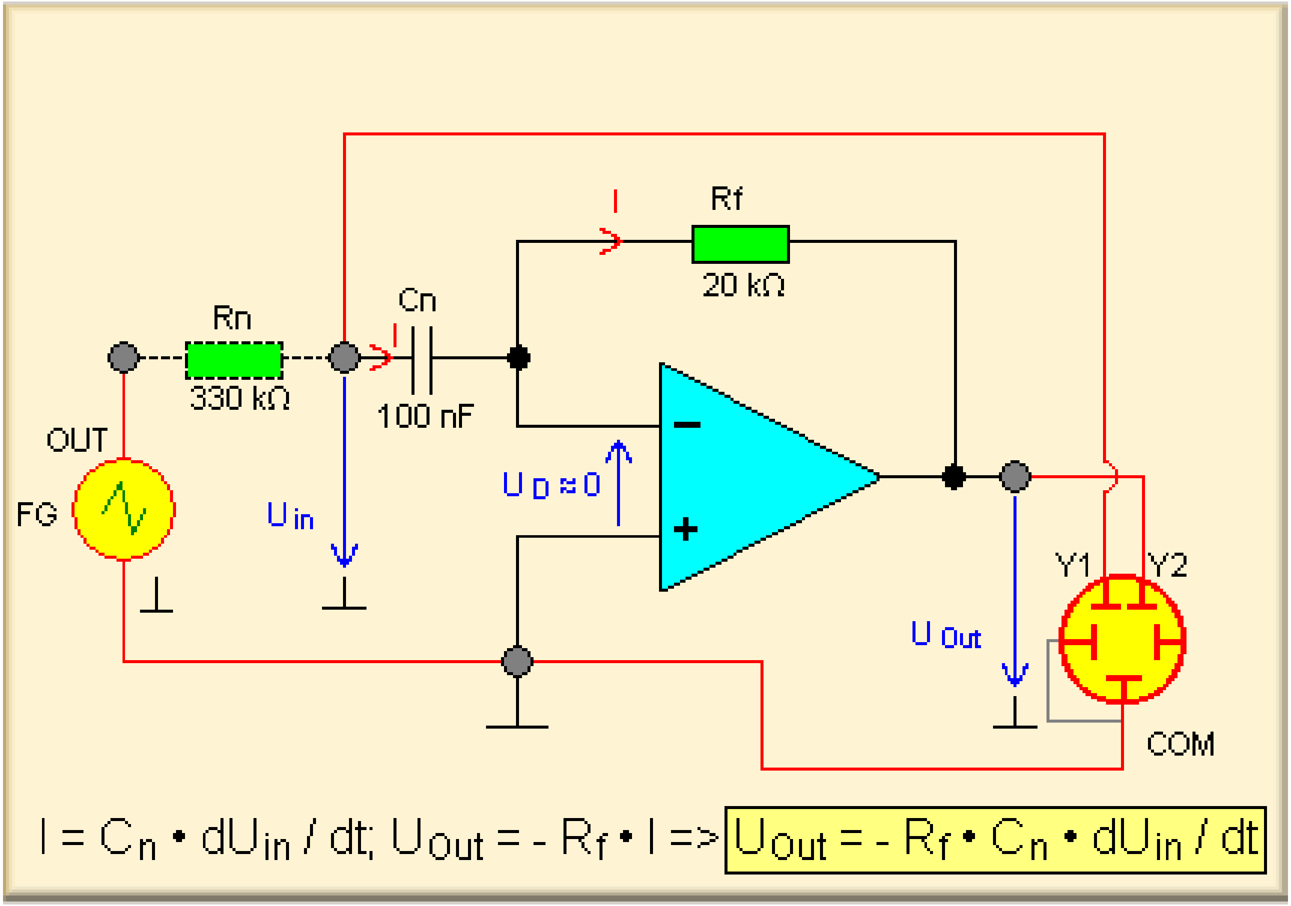
If a path of 100 km is covered in 2 h, this corresponds to a velocity of 50 km/h.

2. The time derivative of work is power.

$$P(t)=\frac{dW(t)}{dt}$$

If work of 2 kWh is performed within 2 h, this corresponds to a power of 1 kW.

8.2 Circuit setup

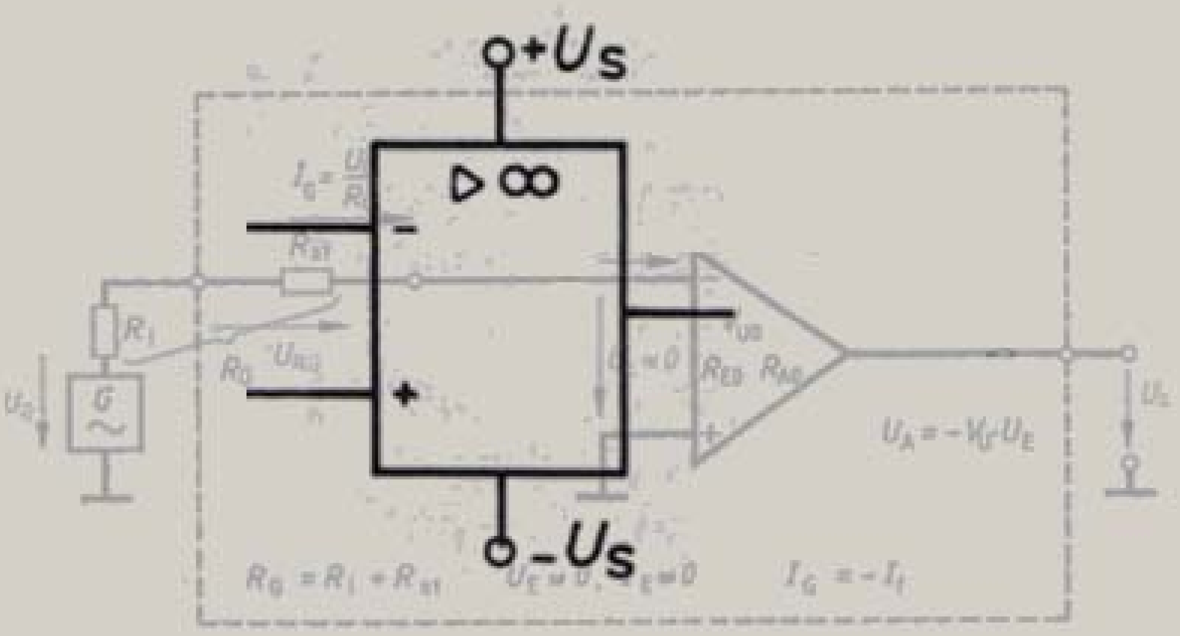


In the case of the differentiator, the charging voltage of the capacitor is the input voltage. The output voltage is the voltage generated by the charging current of the capacitor at R_f.

The resistor R_n enhances the phase margin of the feedback system thus making it stable.

Without R_n the differentiator tends to oscillate.

8.3 Result / application



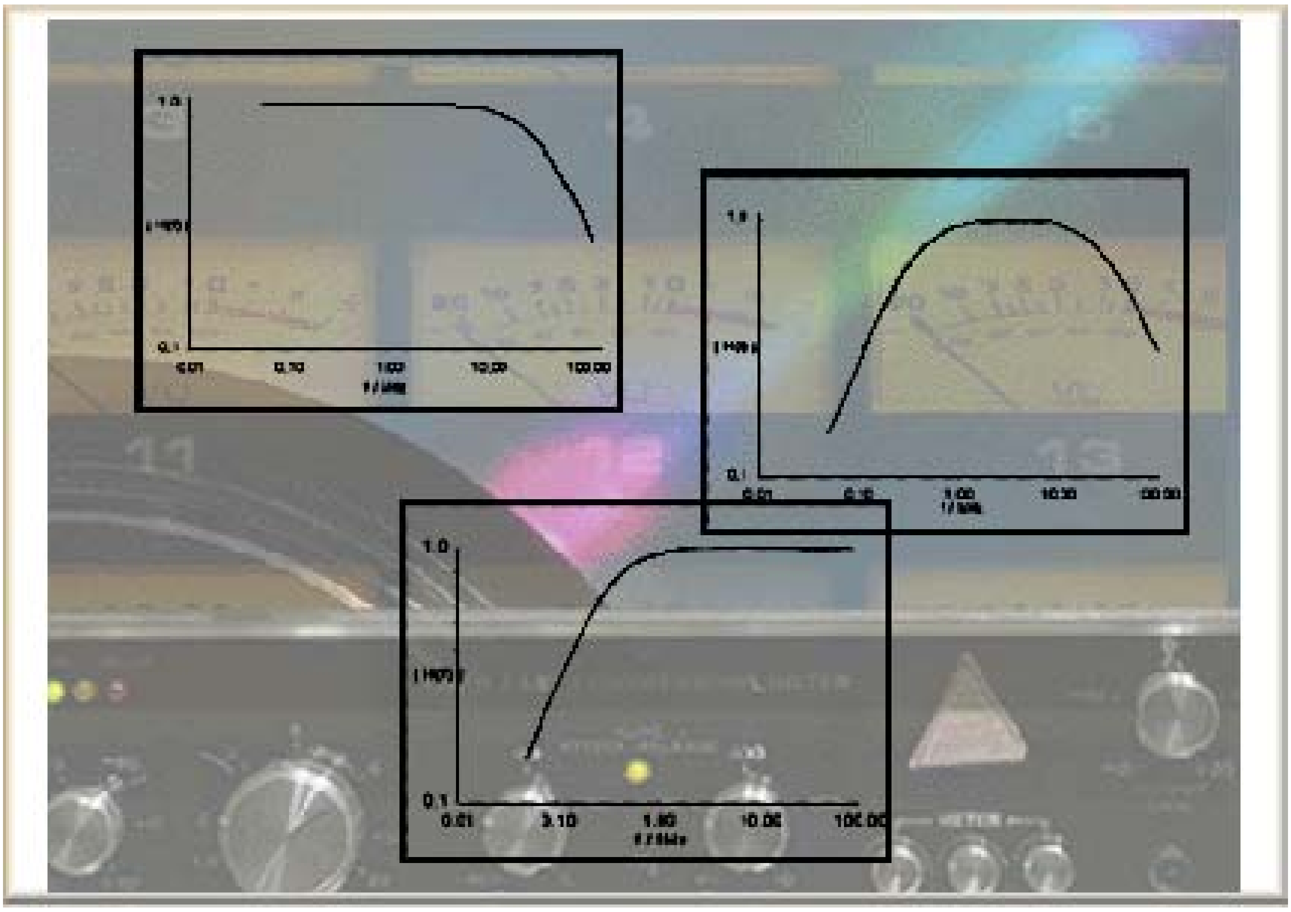
The differentiator used to be employed in analog arithmetical circuits. Today it is almost exclusively employed in control engineering (differential-action controller: D element[1]).

---

[1] **D element**

In control engineering, the D element provides a control variable which is proportional to the differential (time derivative) of the deviation. For details see Courses CT I (Cat.No. 700 82) and CT II (Cat.No. 700 83).

9.1 Introduction



The disadvantage of simple filters[1] consisting of resistors and capacitors is the fact that their characteristics change when they are loaded. This can be prevented by using operational amplifiers. Filters with active components are also called "active filters".

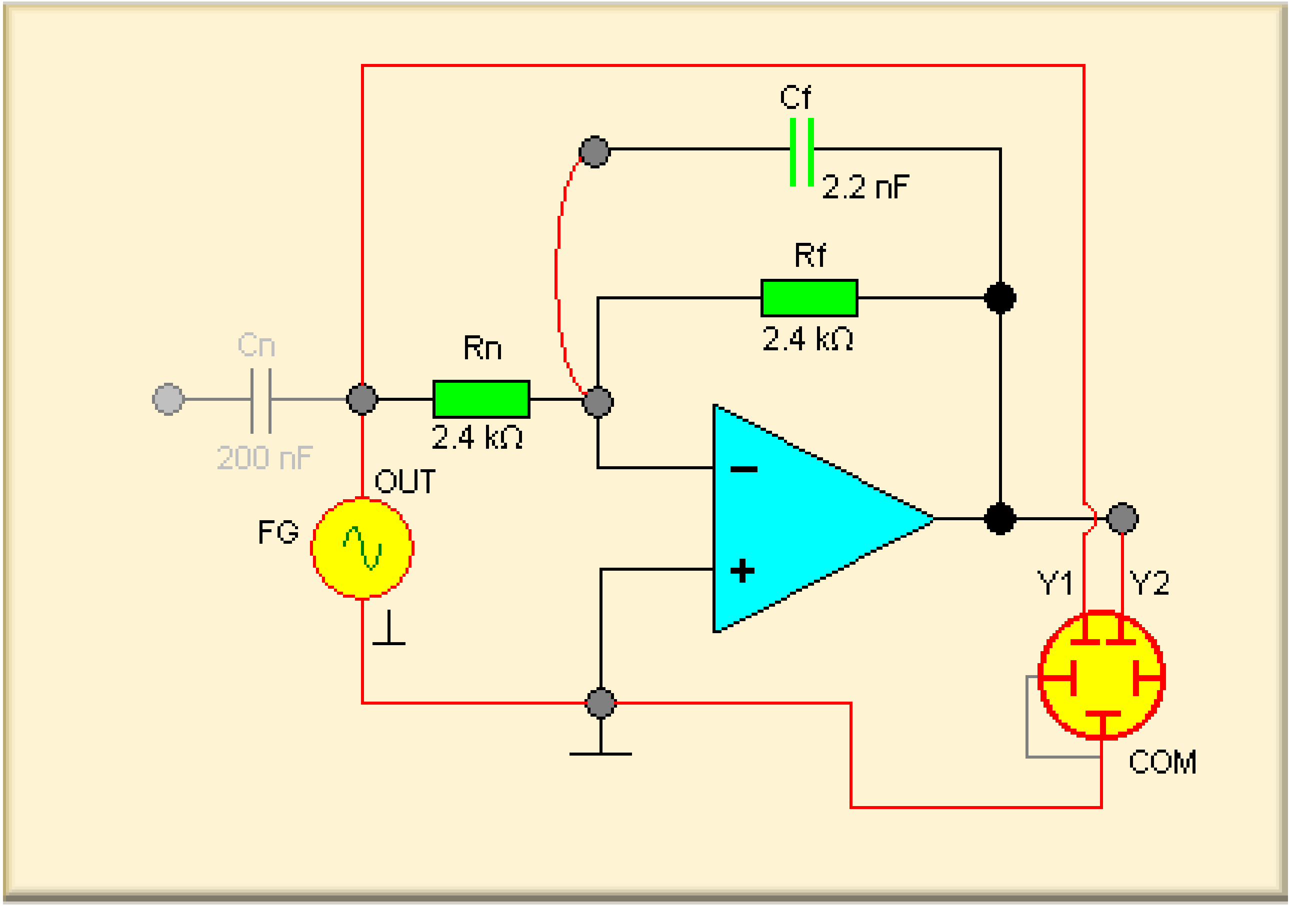
The setup of active filters is based on the principle of the inverting amplifier, whereby the resistances R_n and R_f are exchanged by frequency dependent impedances.

---

[1] **Filters**

Filters are circuits whose transfer function depends on the frequency. Here the transfer function is subdivided into pass bands and stop bands. The boundary between these bands is given by the cutoff frequency, which is defined as the frequency at which the magnitude of the transfer function is smaller than the pass-band amplitude by 3 dB (a factor of 0.707).

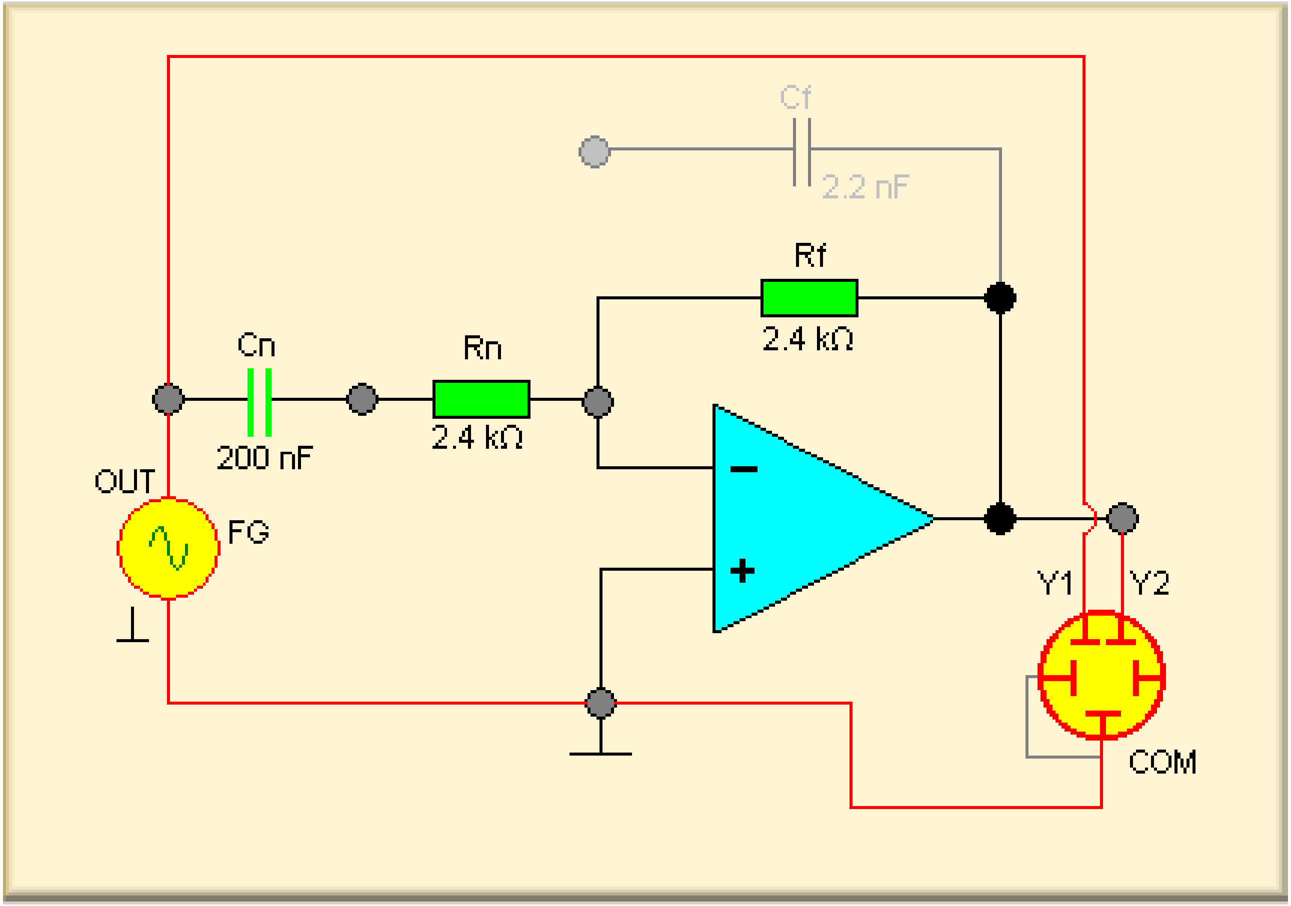
9.2 Low-pass filter



The circuit consists of an inverting amplifier (d.c. gain of –1) with a frequency dependent feedback impedance (R_f and C_f). The impedance of C_f and thereby the feedback impedance decreases with increasing frequency.

It is characteristic of a low-pass filter to pass low frequencies without damping whereas high frequencies are damped.

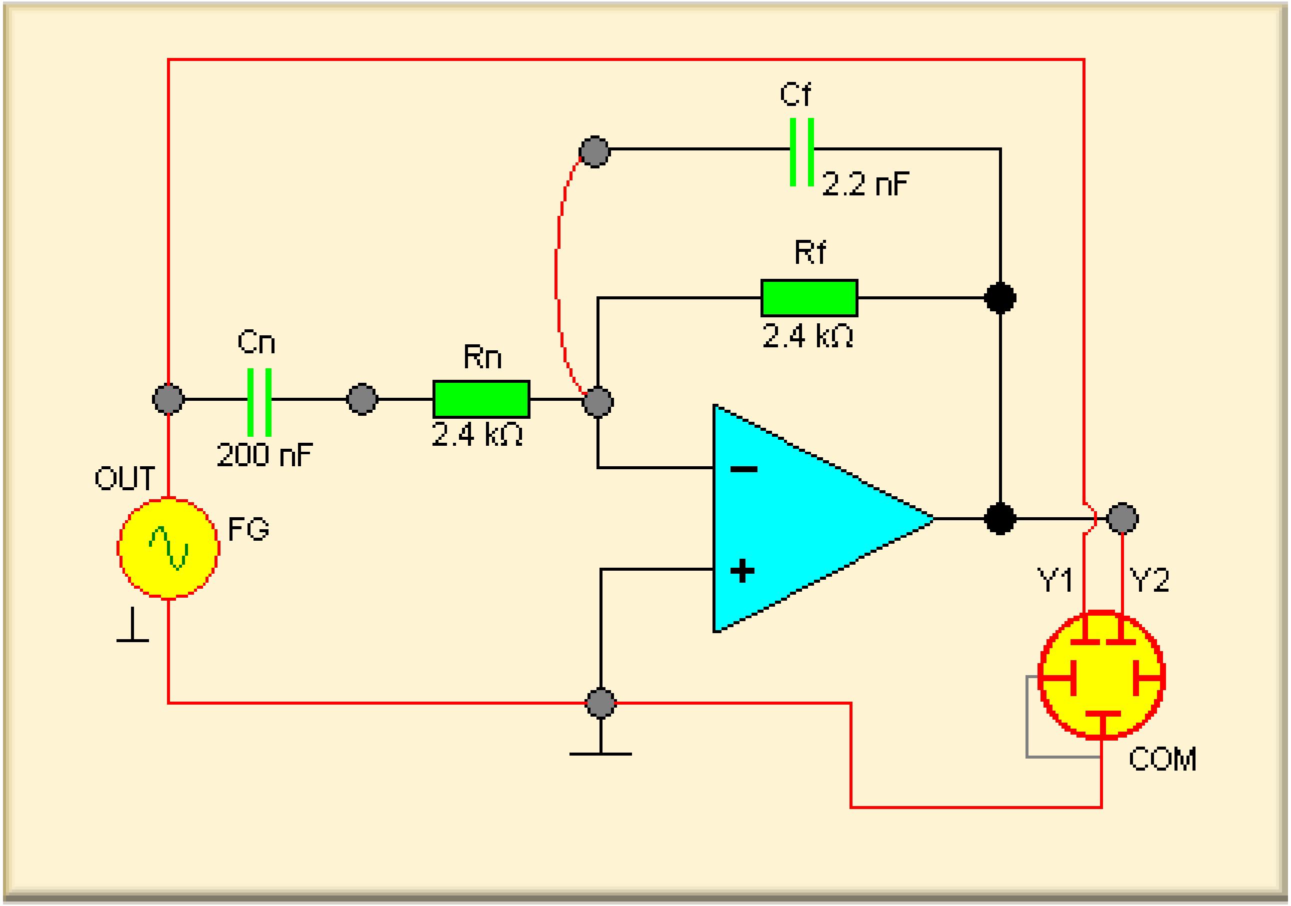
9.3 High-pass filter



The circuit consists of an inverting amplifier with a frequency dependent input impedance (R_n and C_n). The impedance of C_n is high for low frequencies and becomes lower and lower as the frequency increases.

It is characteristic of a high-pass filter to damp low frequencies and to pass high frequencies without damping.

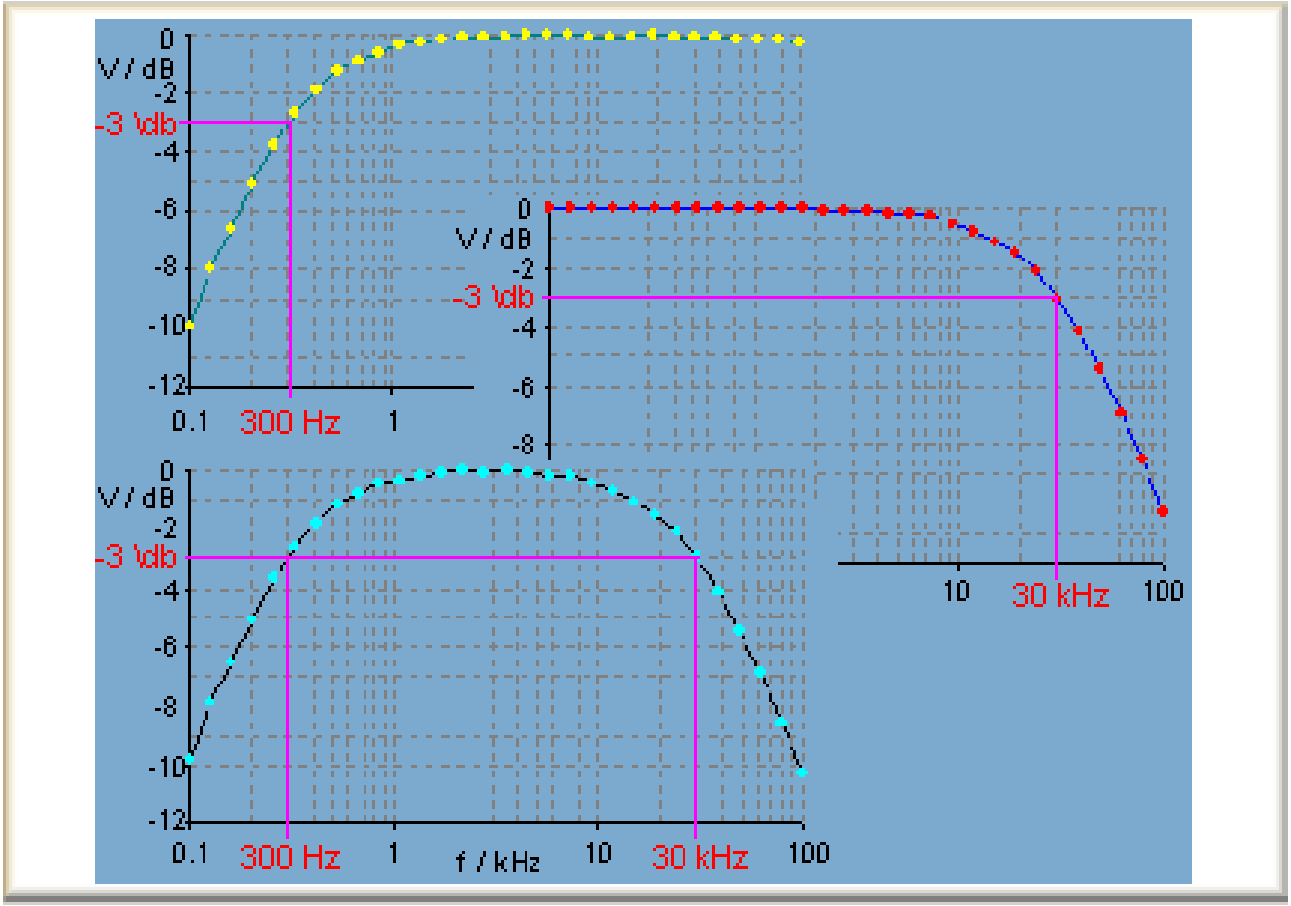
9.4 Bandpass filter



The bandpass filter is a combination of a high-pass and a low-pass filter. Its transfer function corresponds to the product of the two individual transfer functions.

The bandpass filter is employed for passing a certain frequency range.

9.5 Result

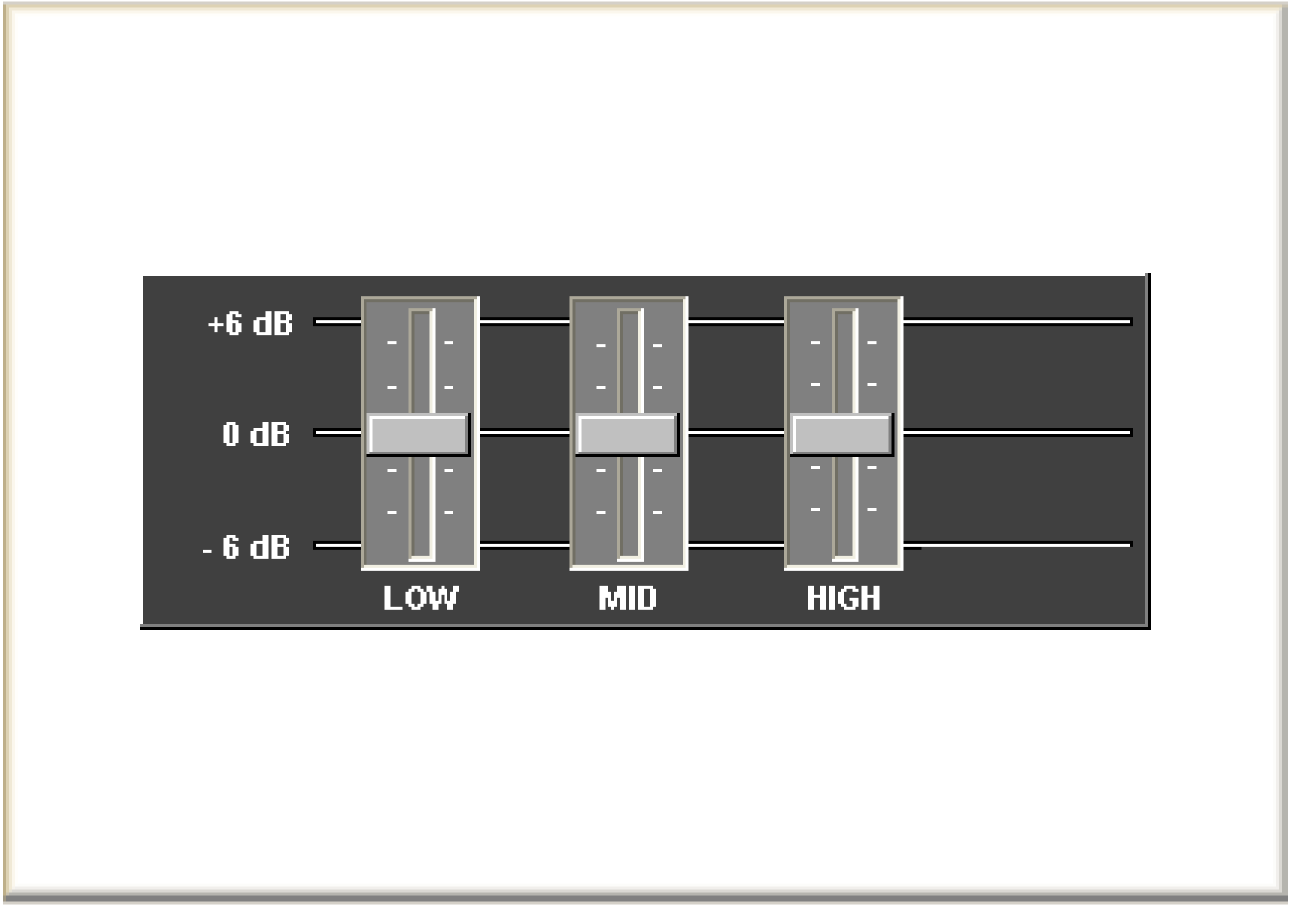


The cutoff frequency of the high-pass filter (HP) is approximately 300 Hz (245 ... 385 Hz)

The cutoff frequency of the low-pass filter (LP) is approximately 30 kHz (24.5 ... 38.5 kHz).

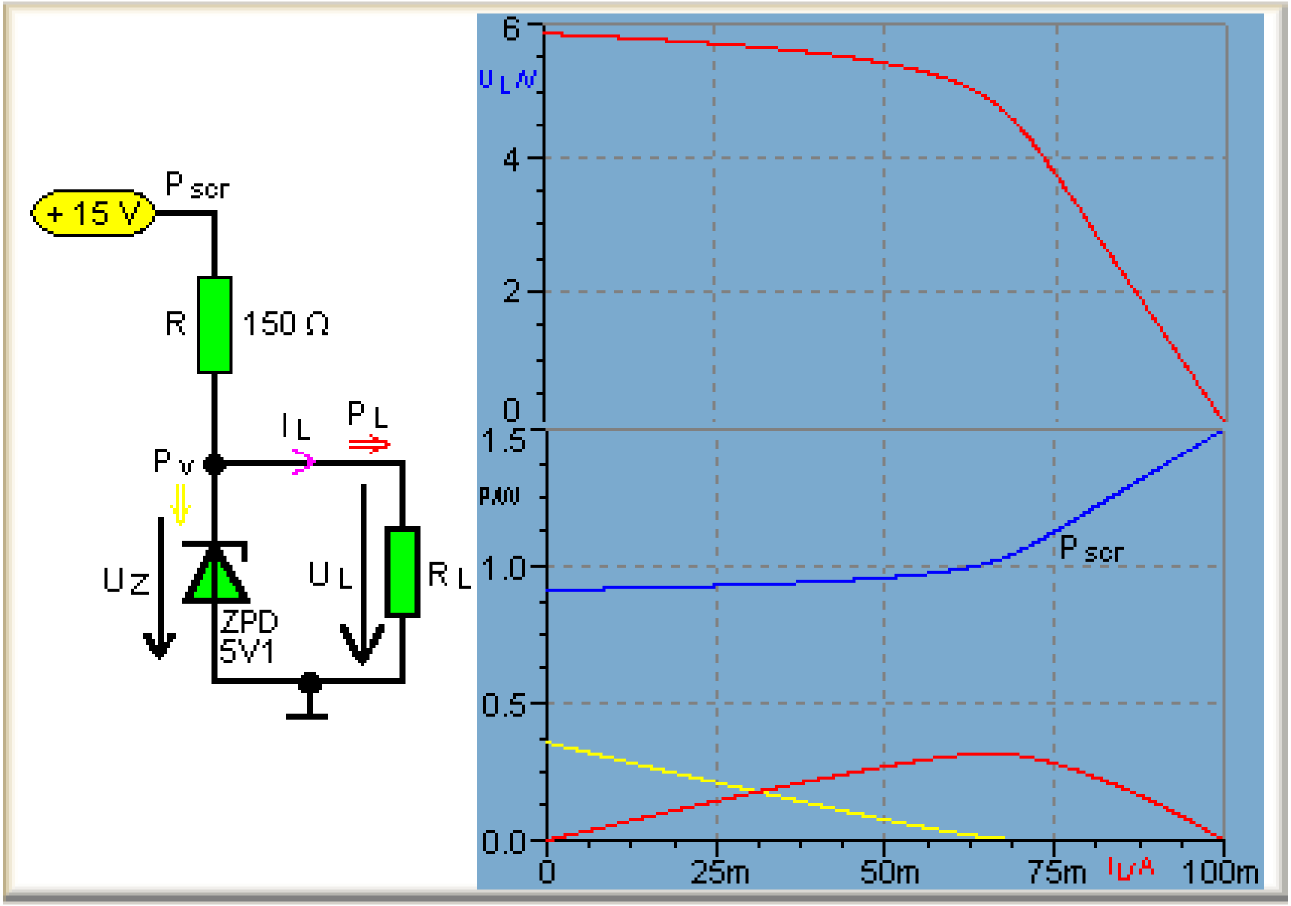
The transfer function of the bandpass filter is obtained by multiplying the transfer functions of the LP and the HP.

9.6 Application



Filter circuits are often used in sound engineering for controlling sounds. With a so-called equalizer frequency ranges can be damped or amplified (highlighted).

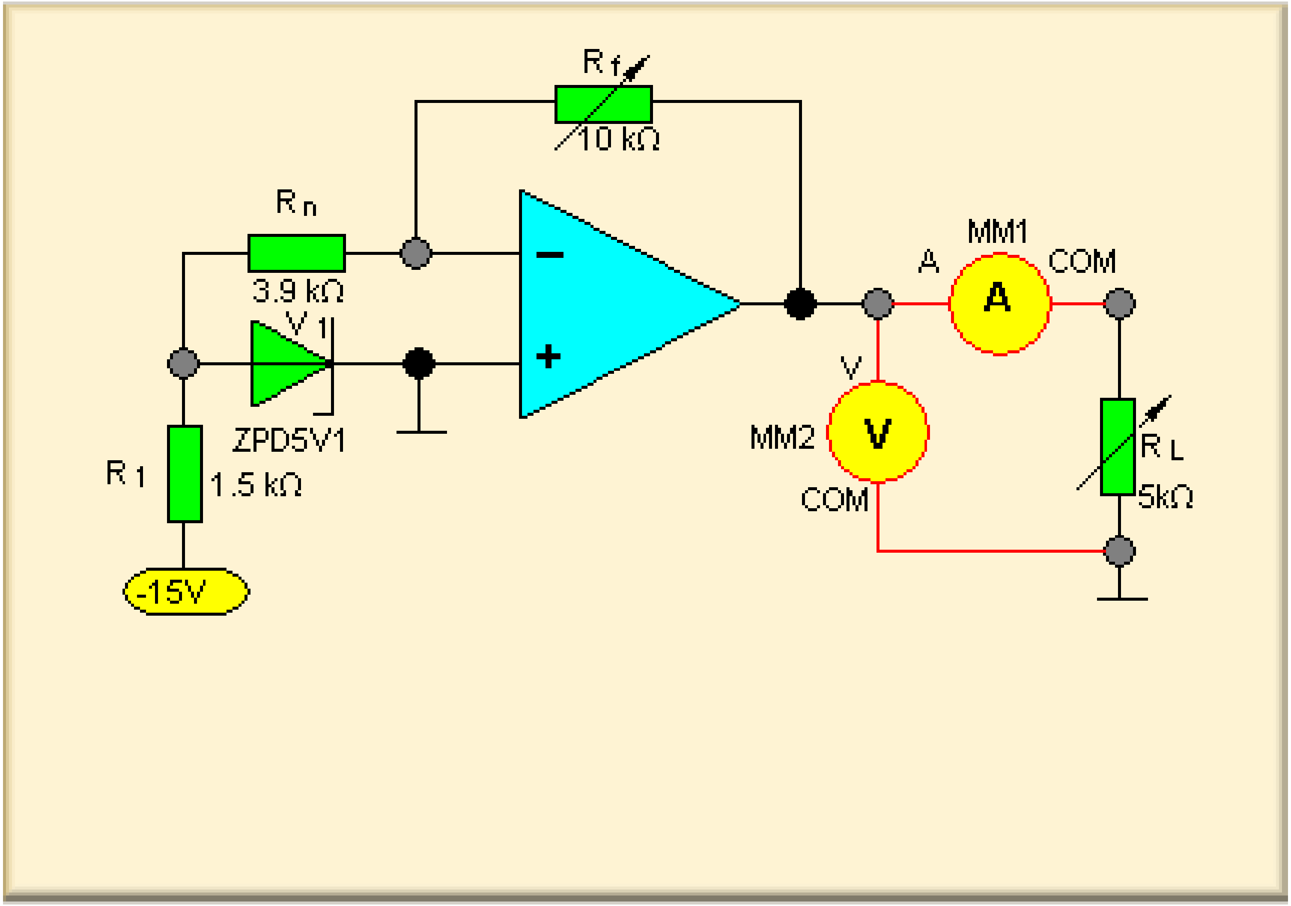
10.1 Introduction



The opposite circuit is a simple constant-voltage source. The disadvantages of this circuit are the high power dissipation and a non-adjustable output voltage.

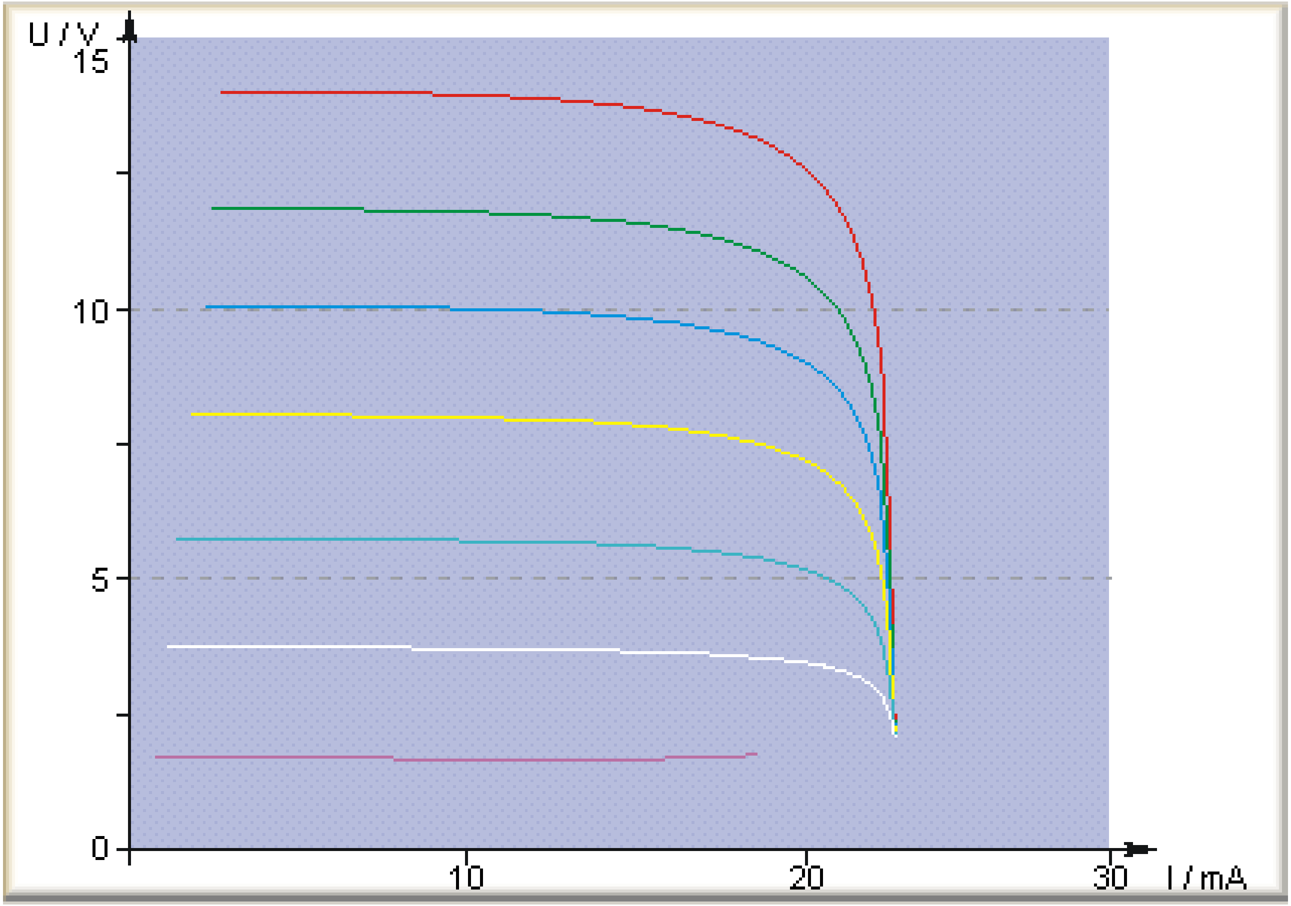
These disadvantages can be circumvented by using operational amplifiers.

10.2 Circuit setup



A negative voltage stabilised by a Zener diode is applied to the inverting branch and causes a constant positive output voltage, which can be adjusted via the gain (R_f / R_n).

10.3 Result



The output voltage (U < 12 V) remains stable until a maximum current (typically approx. 25 mA for the OPA) is exceeded. After that the voltage collapses.

The case of a short circuit is not contained in the curve because the circuit is protected by a 160 Ωresistor in the load branch.

Neither is the case of open-circuit operation contained because the highest load resistance is about 5 kΩ.

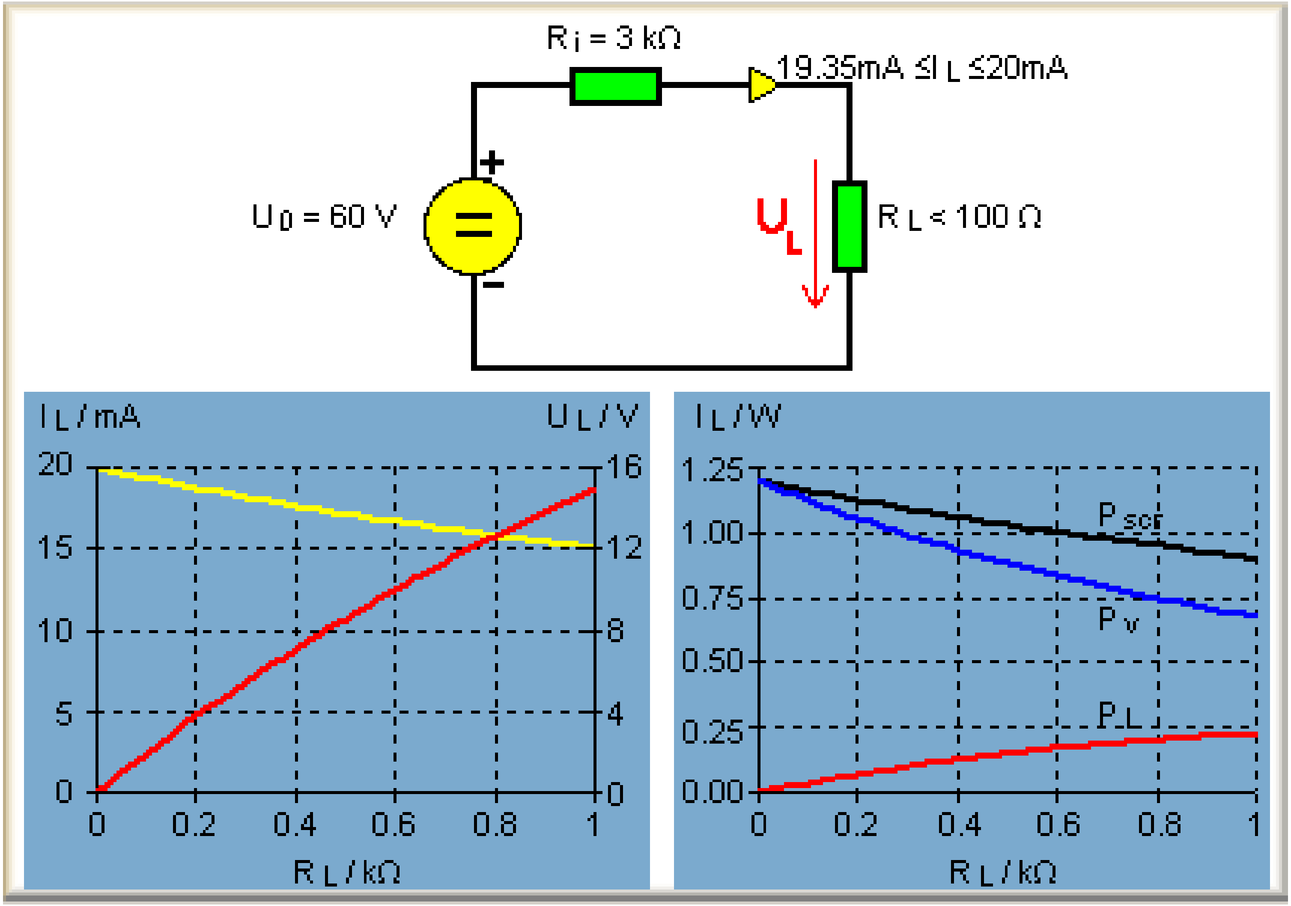
10.4 Application

Constant-voltage sources are employed in stabilised power supplies and for supplying components and circuits that are sensitive to voltage fluctuations.

Constant-voltage sources are very common and can be found in stabilised power supplies.

In almost all power supplies the output voltage is stabilised by means of various types of circuits.

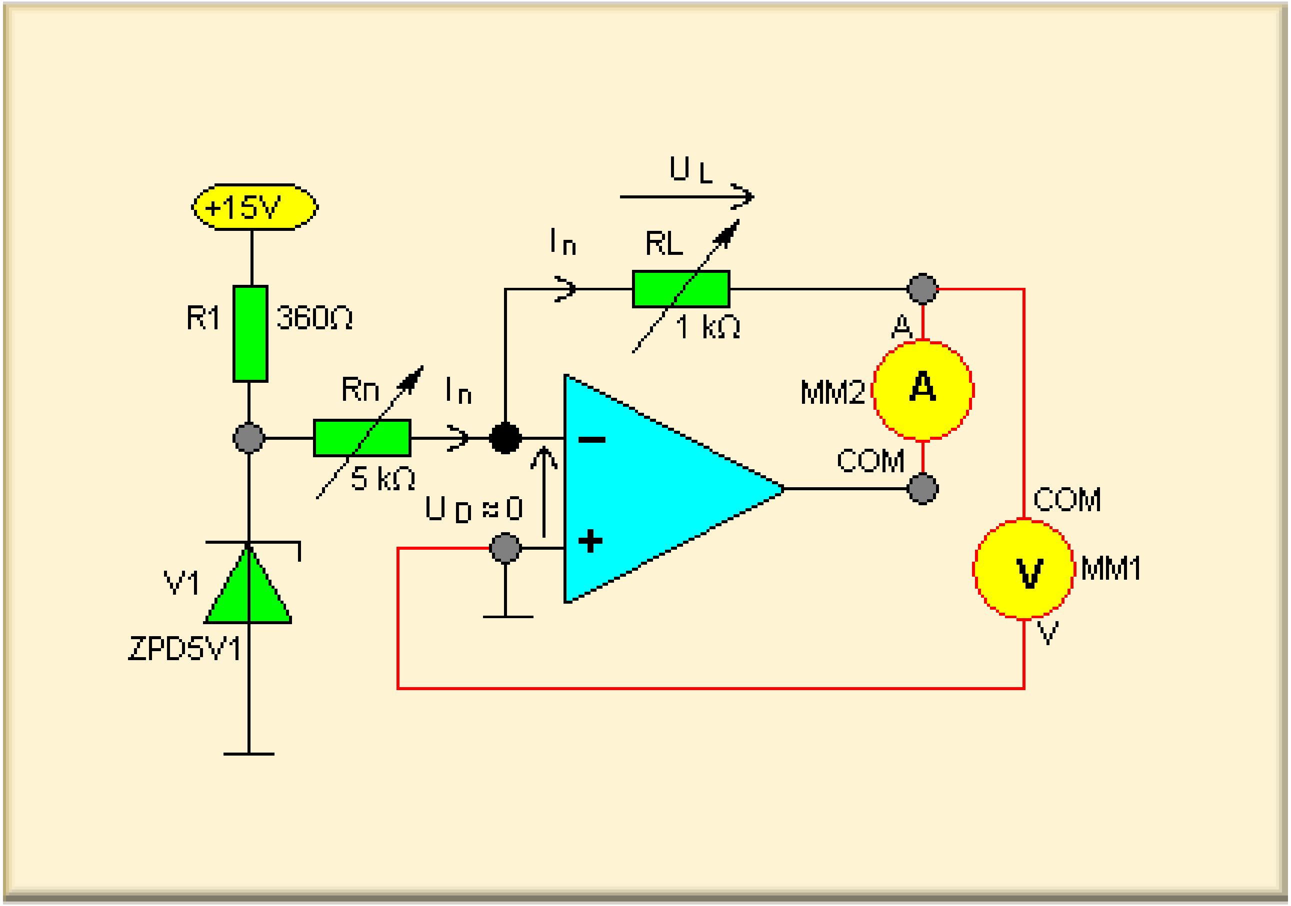
11.1 Introduction



A simple constant-current source can be realised, e.g., by series connection of a high-ohmic resistor R_i and a voltage source U_0. If the short-circuit current shall not be minute, the voltage U_0 has to be very high. Moreover, the load resistance has to be considerably smaller than R_i. Another disadvantage is the high power dissipation (P_D) in the series resistor R_i.

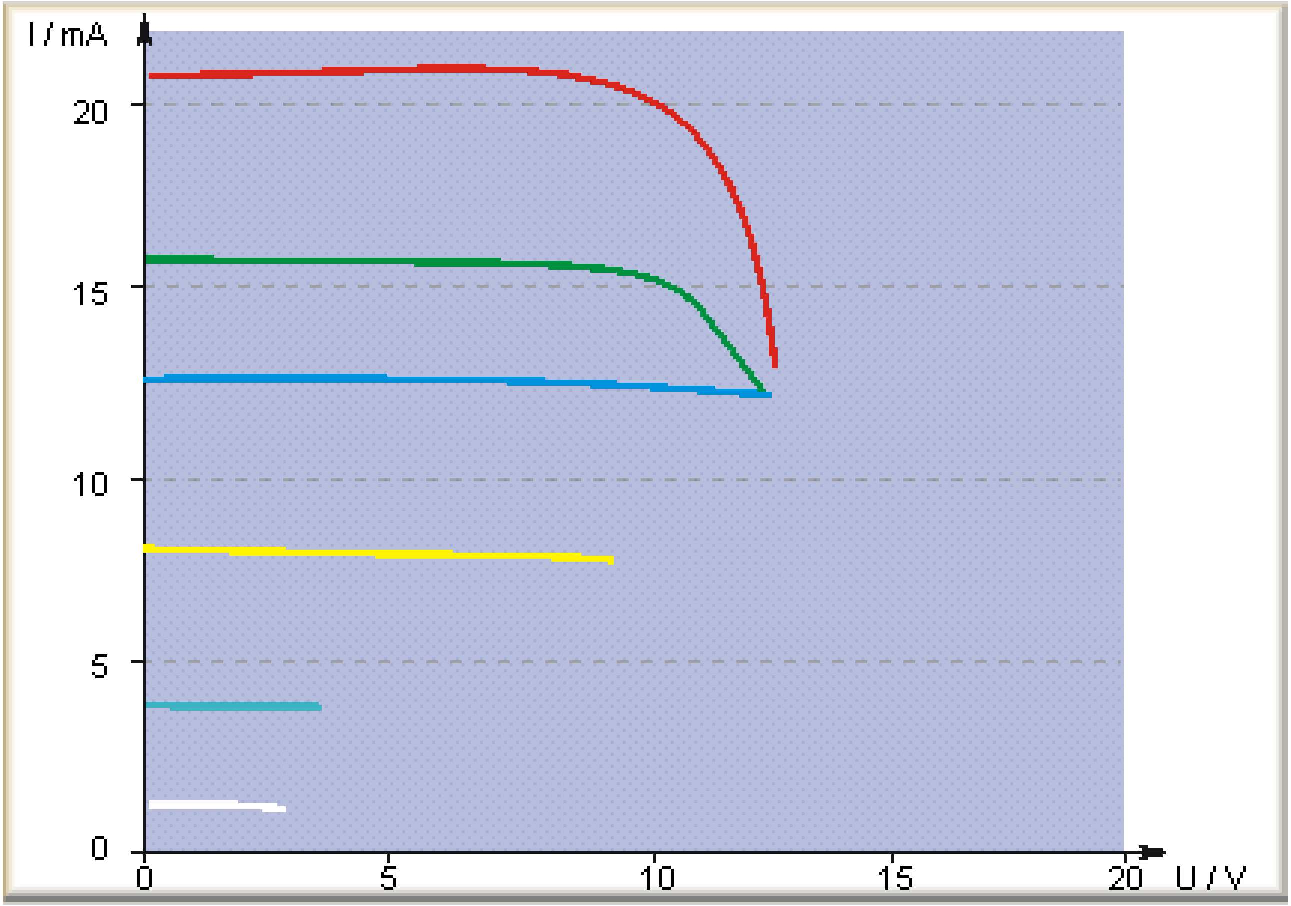
These problems can be circumvented by using operational amplifiers.

11.2 Circuit setup



As the load resistor R_L is in the feedback branch, the output voltage is readjusted when the load changes. The current generated by the output voltage and the load resistor is therefore constant. It is equal to the current adjusted via the Zener voltage and R_n.

11.3 Result



The load current remains constant until the voltage limit of the OPA is reached (–12 ... –13 V). After that the load current collapses.

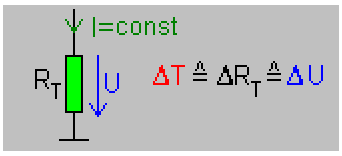
With the purpose of protection the current is limited to approx. 20 mA by a series resistor of 240 Ω.

11.4 Application

Constant-current sources are employed in stabilised power supplies for supplying components or circuits that are sensitive to current fluctuations.

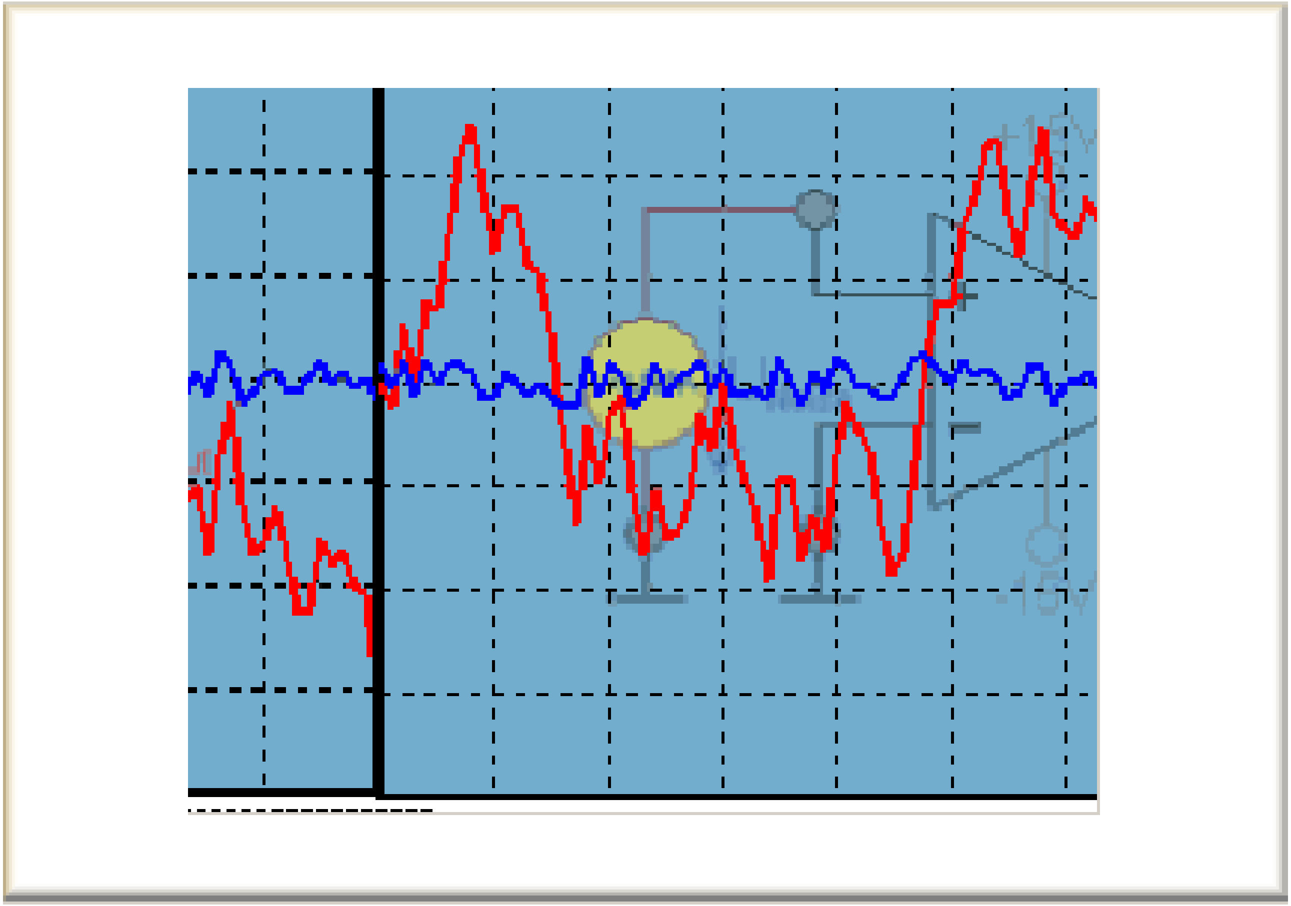
Constant currents are required, e.g., for Zener diodes (the operating point is adjusted with the current). In temperature measuring circuits[1] the temperature change can be determined with temperature-dependent resistors by measuring the voltage if a constant current is applied.

[1] **Temperature Measuring Circuits**



A constant current is injected via a temperature-dependent resistor. If the value of the resistance changes due to a change in the ambient temperature, this leads to a change in the voltage drop at the resistor. Thus the change in temperature can be deduced from the change in the voltage drop. The constant current has to be chosen so that the self-heating of the resistor due to its own power dissipation remains small.

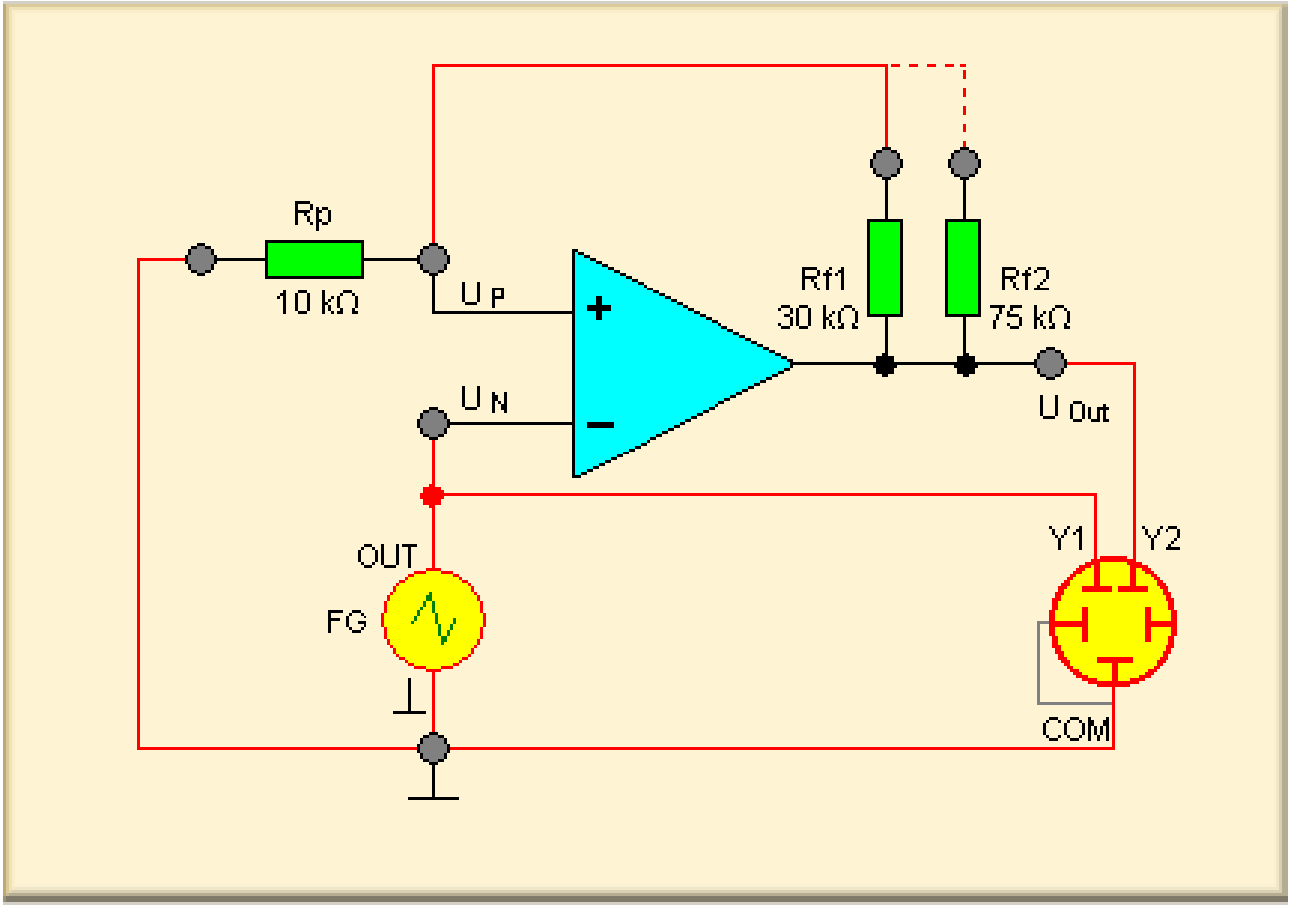
12.1 Introduction



The comparator has a vital disadvantage: If the input signals are noisy, the state of the output changes several times near the switching point.

This can be avoided if a comparator with hysteresis is used. Such a circuit is also called a **Schmitt trigger**.

12.2 Inverting Schmitt trigger



The positive feedback leads part of the output voltage U_{out} back to the non- inverting input (U_P). Therefore the input voltage at the inverting input (U_N) has to exceed or fall below a certain value in order that the sign of the output voltage changes. The following switching conditions are obtained:

$$Uin_{off} > Uout_{\text{max}} \frac{R_p}{R_p + R_{f_i}}$$

$$Uin_{off} > 0$$

for the change from $U_{\text{out max}}$ to $U_{\text{out min}}$ and

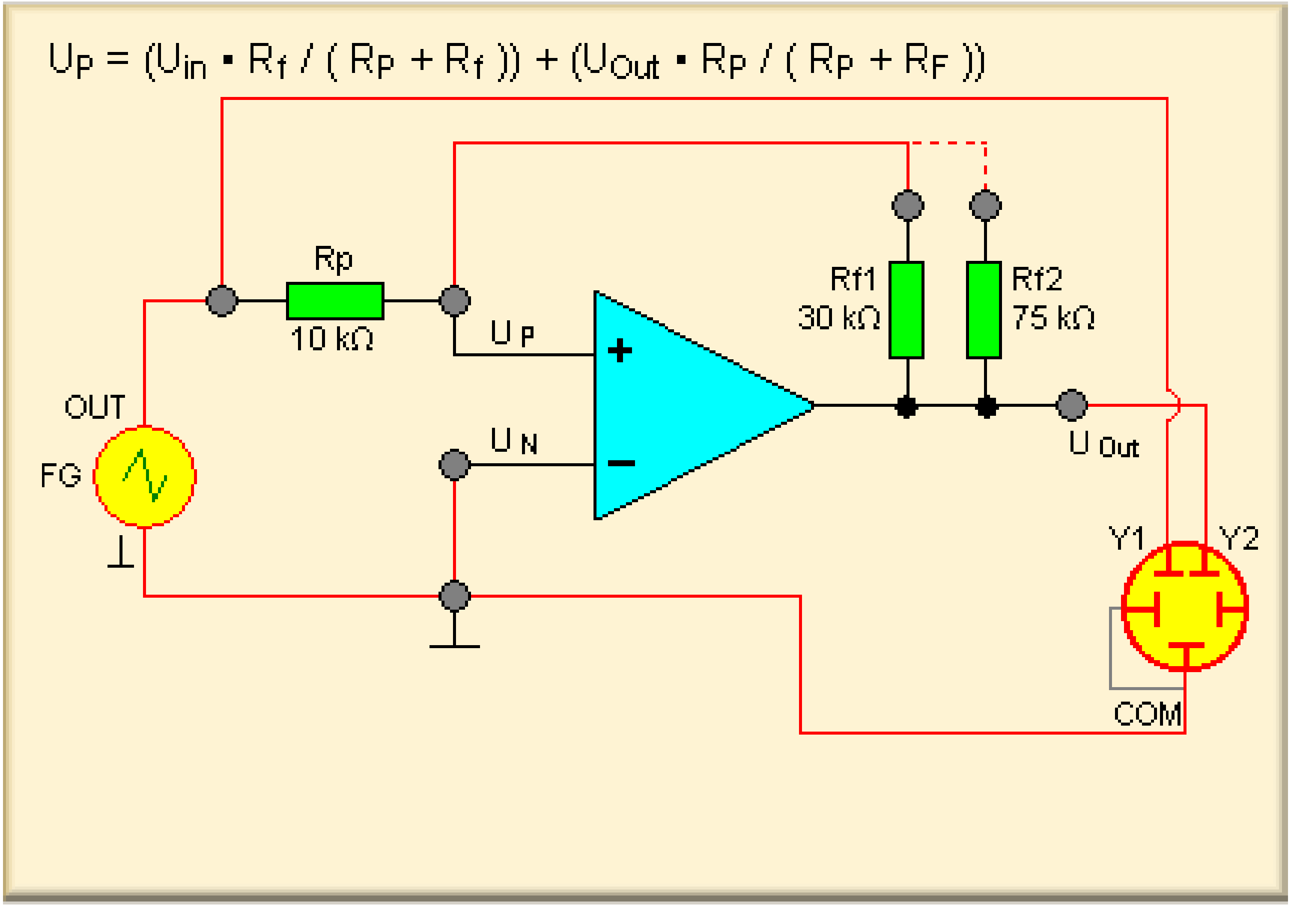
$$Uin_{on} < Uout_{\text{min}} \frac{R_p}{R_p + R_{f_i}}$$

$$Uin_{on} < 0$$

for the change from $U_{\text{out min}}$ to $U_{\text{out max}}$.

The positive feedback leads to a region where the Schmitt trigger does not operate. This region is called hysteresis.

12.3 Non-inverting Schmitt trigger



The potential U_p can be calculated according to the principle of superposition. Here R_p and R_{fi} form a voltage divider.

From this the switching conditions are obtained:

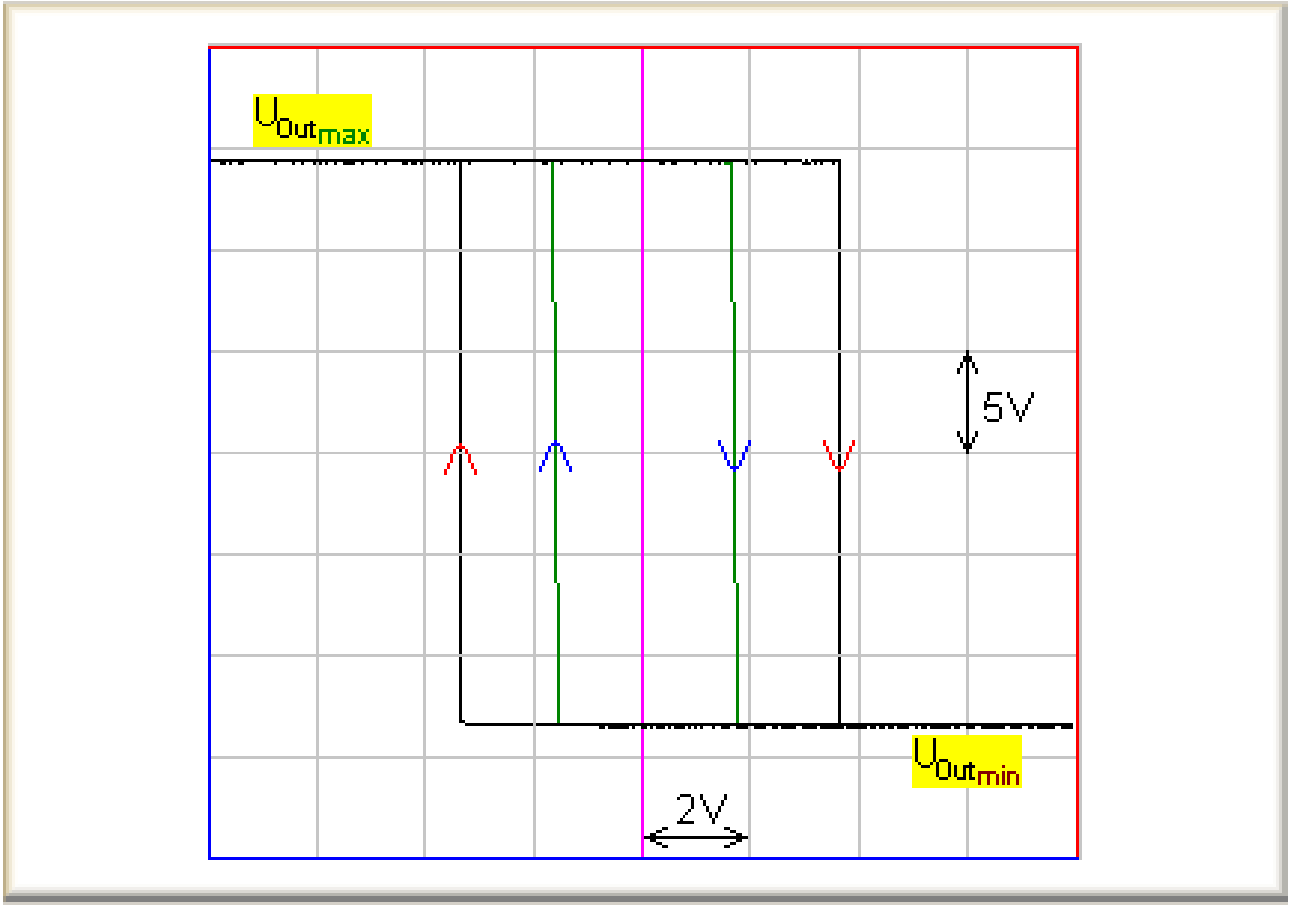
$$Uin_{on} > -Uout_{min} \cdot \frac{R_p}{R_{fi}} \, (> 0)$$

for the change from $U_{\text{out min}}$ to $U_{\text{out max}}$.

$$Uin_{off} < -Uout_{max} \cdot \frac{R_p}{R_{f_i}} \, (< 0)$$

for the change from $U_{\text{out max}}$ to $U_{\text{out min}}$.

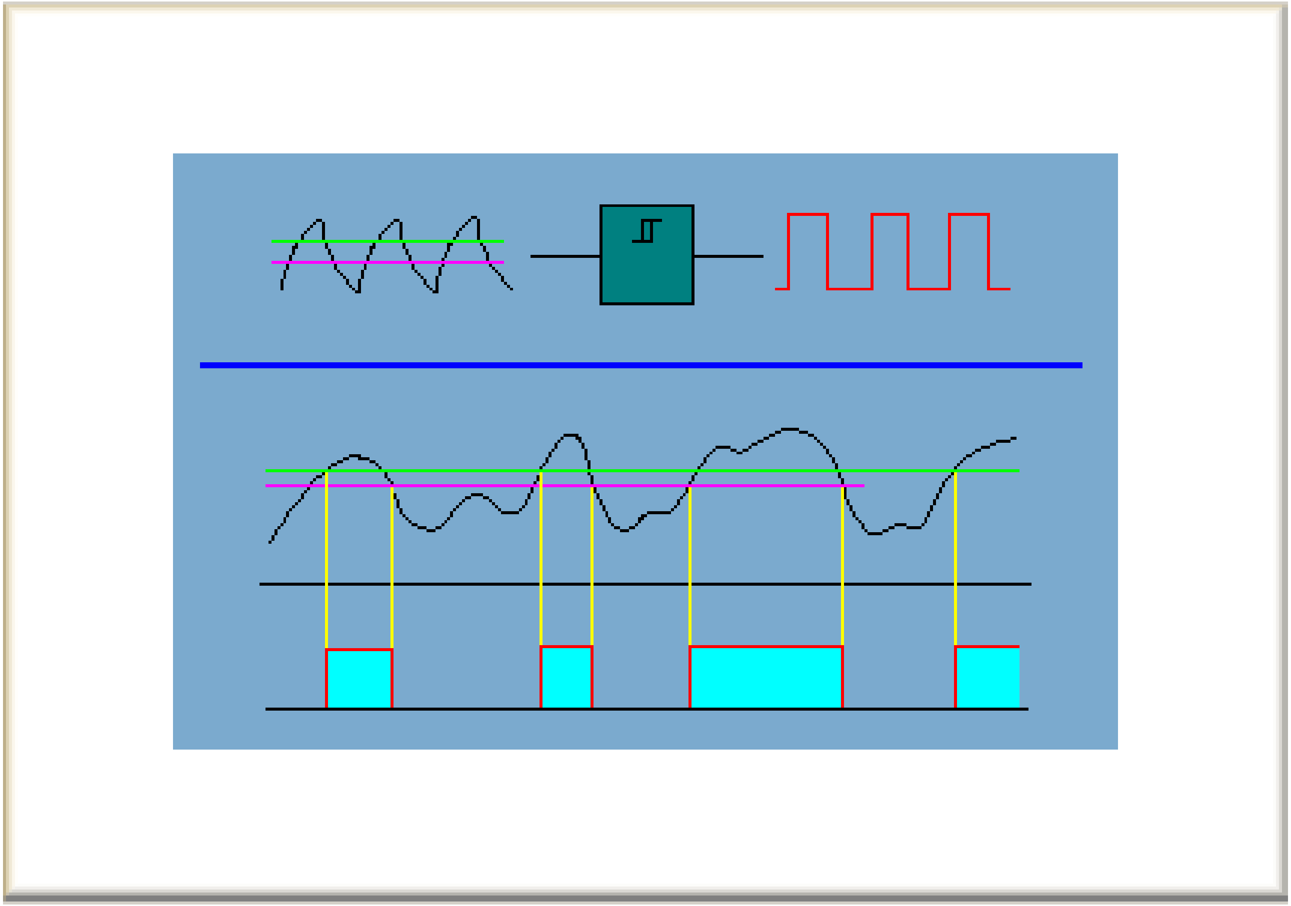
12.4 Evaluation



The hysteresis values do not depend on the resistances alone, but also on the limits of the OPA's dynamic range. Therefore a slightly asymmetric hysteresis results because the negative limit is usually smaller than the positive one by 1 V.

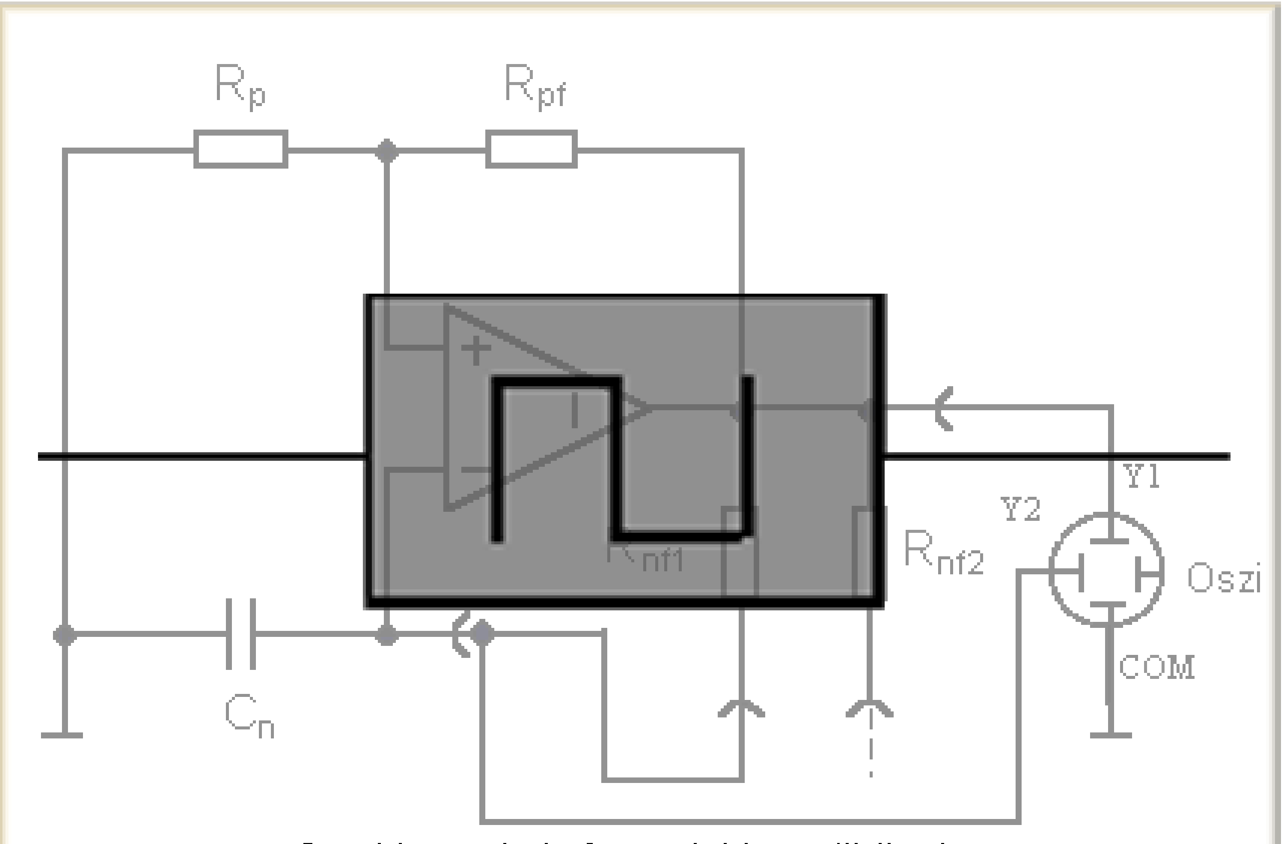
In the case of an inverting Schmitt trigger, the output is (apart from the hysteresis region) positive if U_{in} is negative and negative if U_{in} is positive. A non-inverting Schmitt trigger has just the opposite behaviour.

12.5 Application



The Schmitt trigger is employed, e.g., in communications engineering in order to convert noisy digital signals into "clean" rectangular signals. Schmitt triggers are, among other things, also contained in the serial interfaces of a computer.

13.1 Introduction

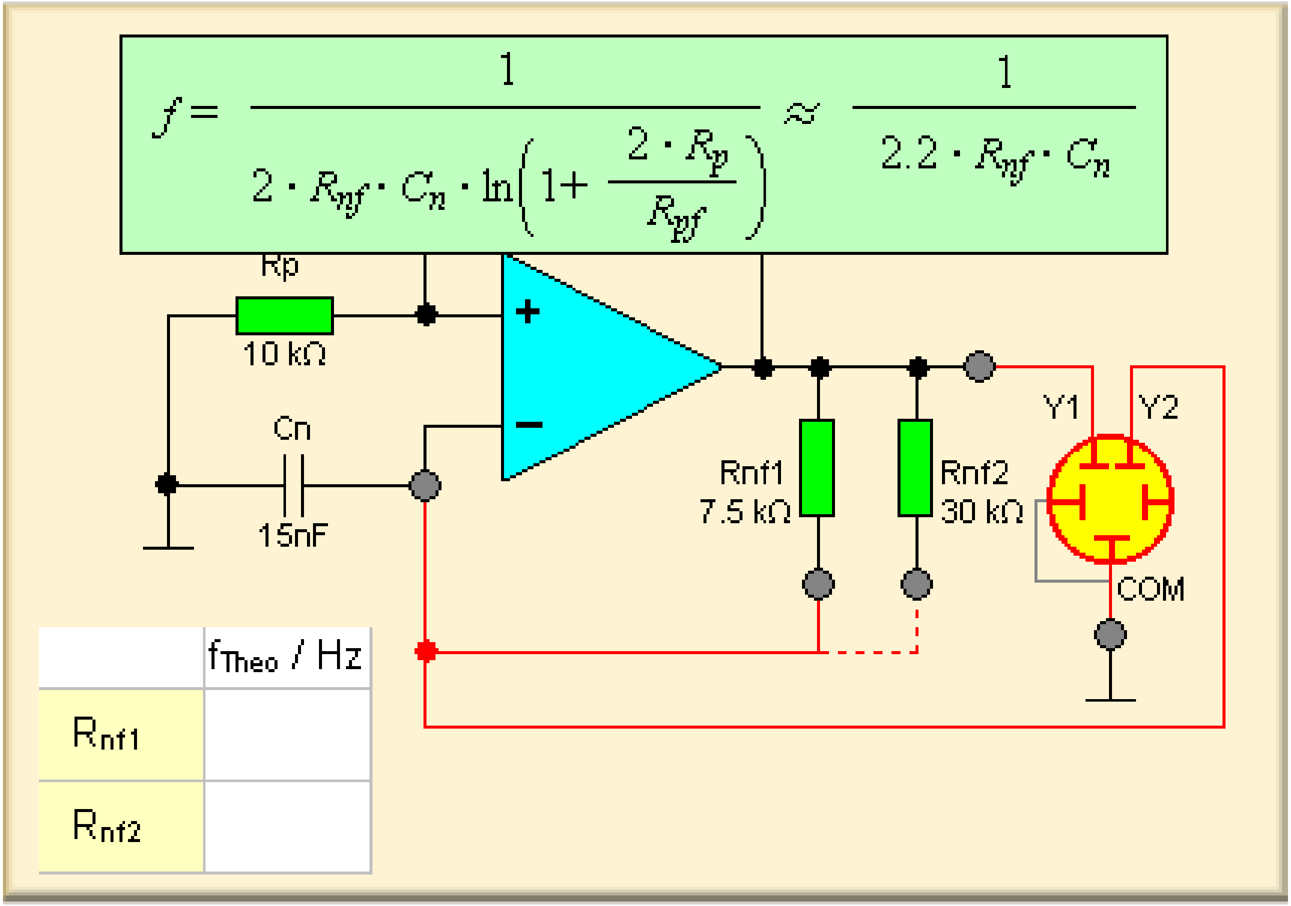


Graphic symbol of an astable multivibrator

The astable multivibrator generates a rectangular signal with constant amplitude and frequency without external excitation. That means it is an oscillating circuit.

The multivibrator contains a time-determining element, in this case an RC element, which influences the frequency through its time constant.

13.2 Circuit setup

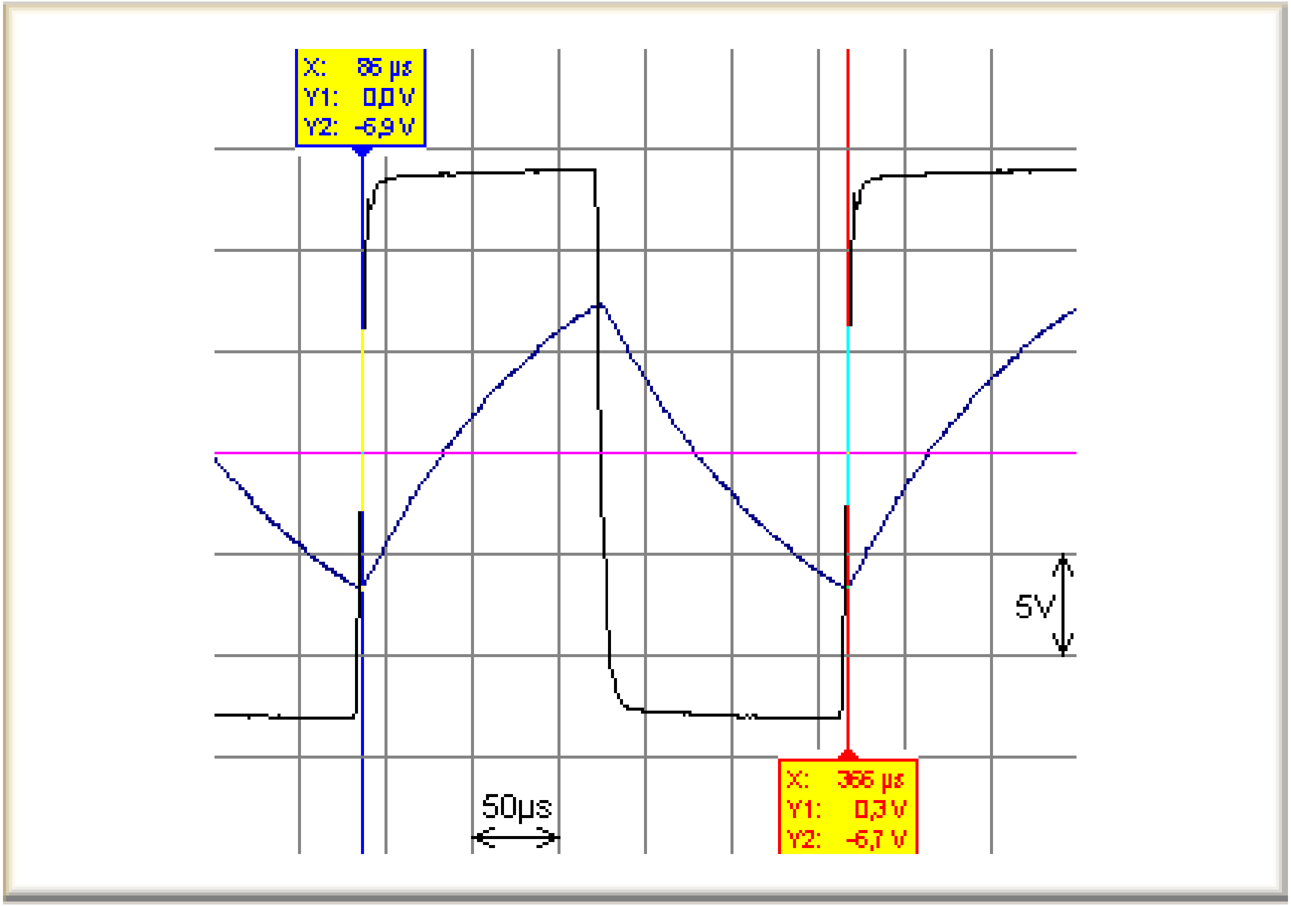


$$f = \frac{1}{2\cdot R_{nf}\cdot C_n\cdot \ln\left(1+\frac{2\cdot R_p}{R_{pf}}\right)} \approx \frac{1}{2.2\cdot R_{nf}\cdot C_n}$$

	f_{Theo} / Hz
R_{nf1}	
R_{nf2}	

The multivibrator has a positive as well as a negative feedback. The negative feedback branch consists of the RC element R_{nf} and C_n, and the positive feedback branch of the voltage divider R_{pf} and R_p, which fixes the threshold voltages of the hysteresis. The frequency of the system depends on the voltage division ratio and the time constant of the RC element.

13.3 Result



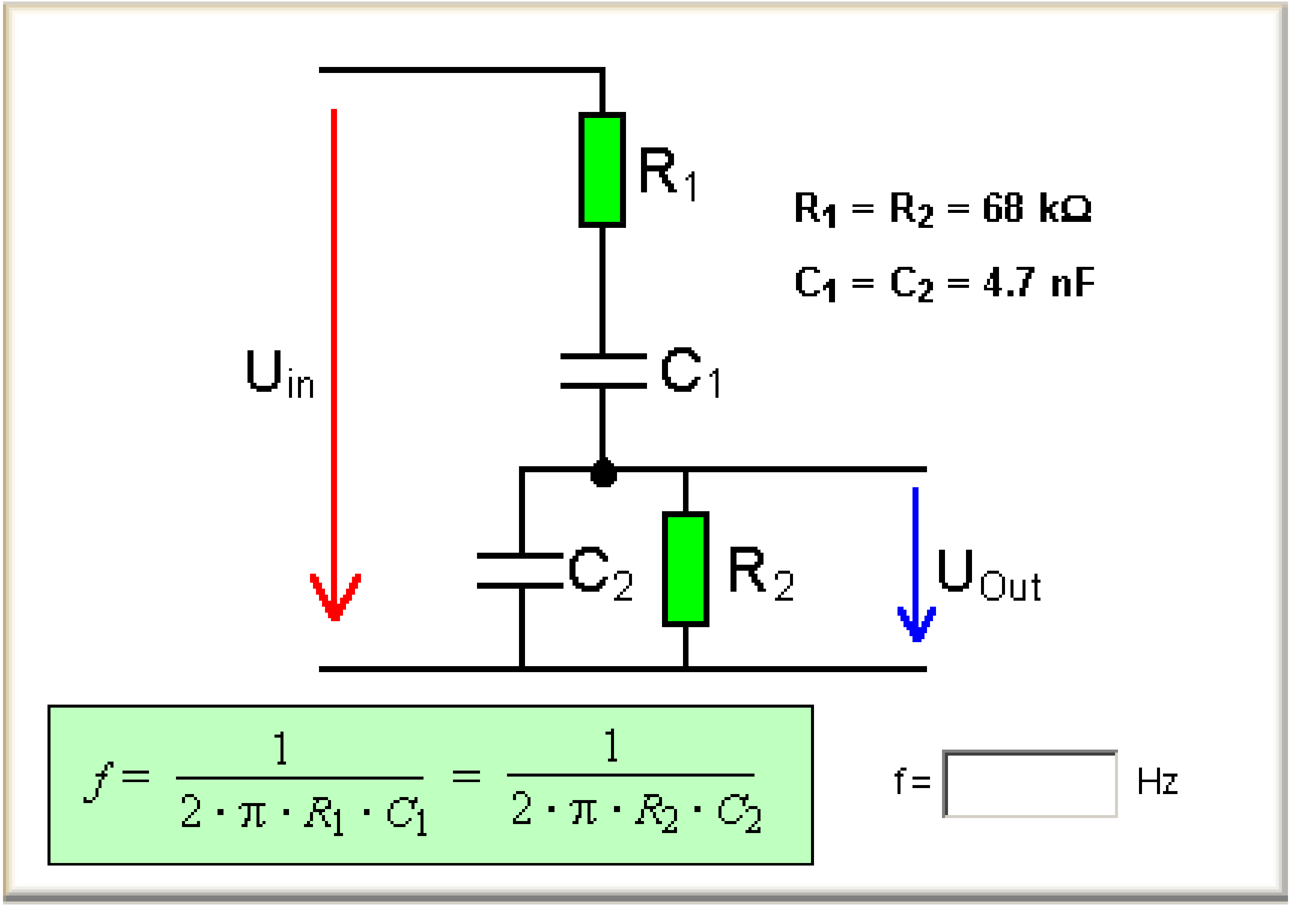
The output signal is a rectangular function. The potential at the inverting input corresponds to the charging and discharging curve of an RC element.

The frequencies are nominally **4 kHz** (with R_{f1} = 7.5 kΩ) and **1 kHz** (with R_{f2} = 30 kΩ). They are subject to spread because of tolerances of the components.

13.4 Application

Astable multivibrators are employed in function generators. In digital engineering clock pulses for low clock frequencies are generated with astable multivibrators.

14.1 Introduction

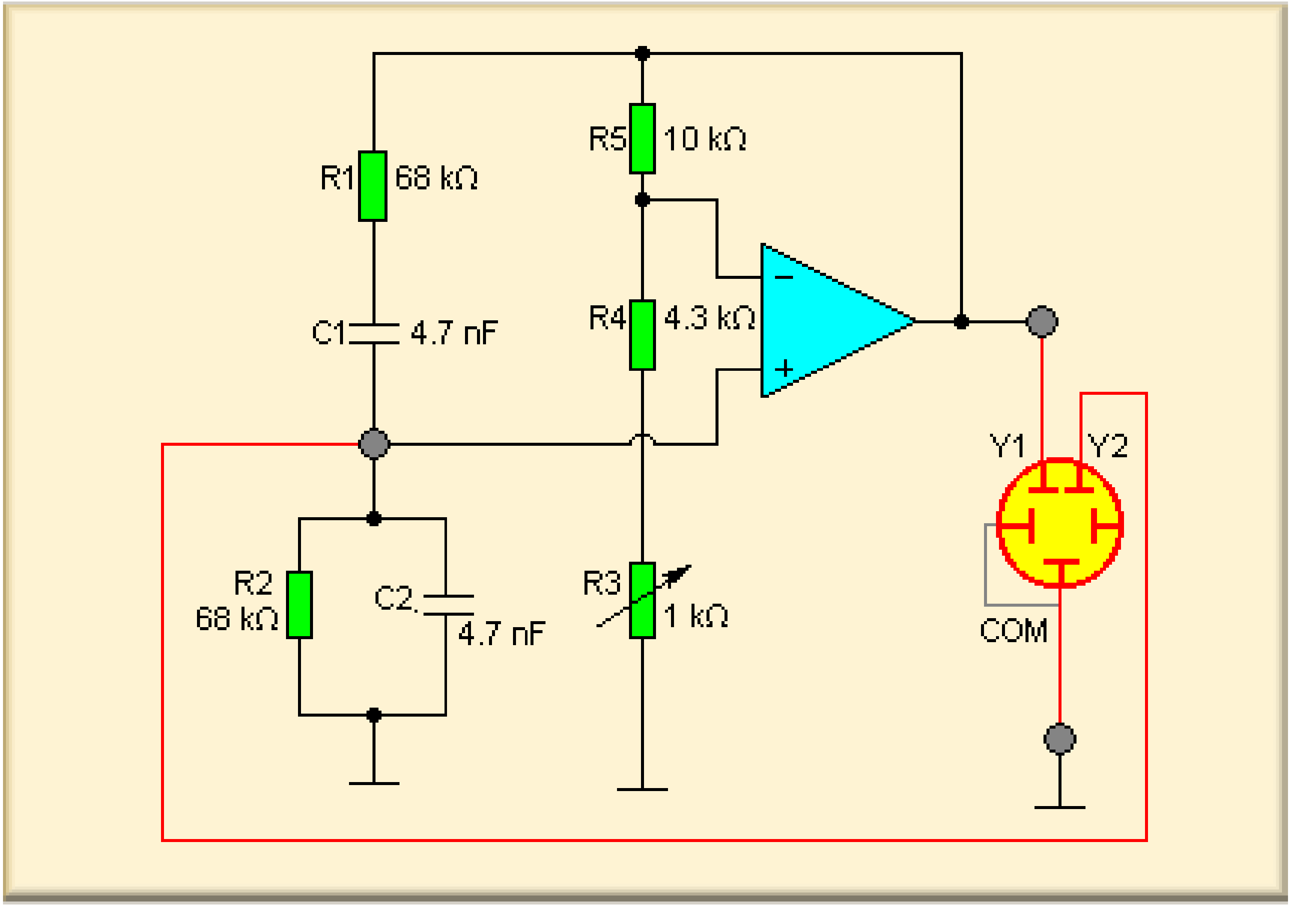


$$f = \frac{1}{2 \cdot \pi \cdot R_1 \cdot C_1} = \frac{1}{2 \cdot \pi \cdot R_2 \cdot C_2}$$

In the Wien bridge oscillator the Wien bridge is used as a frequency dependent voltage divider. At the frequency determined by the RC elements the output voltage U_{out} of the Wien bridge has its maximum value and the phase difference between U_{out} and U_{In} is 0°.

As the RC filter is inserted in the positive feedback of the operational amplifier, it determines the oscillating behaviour of the system.

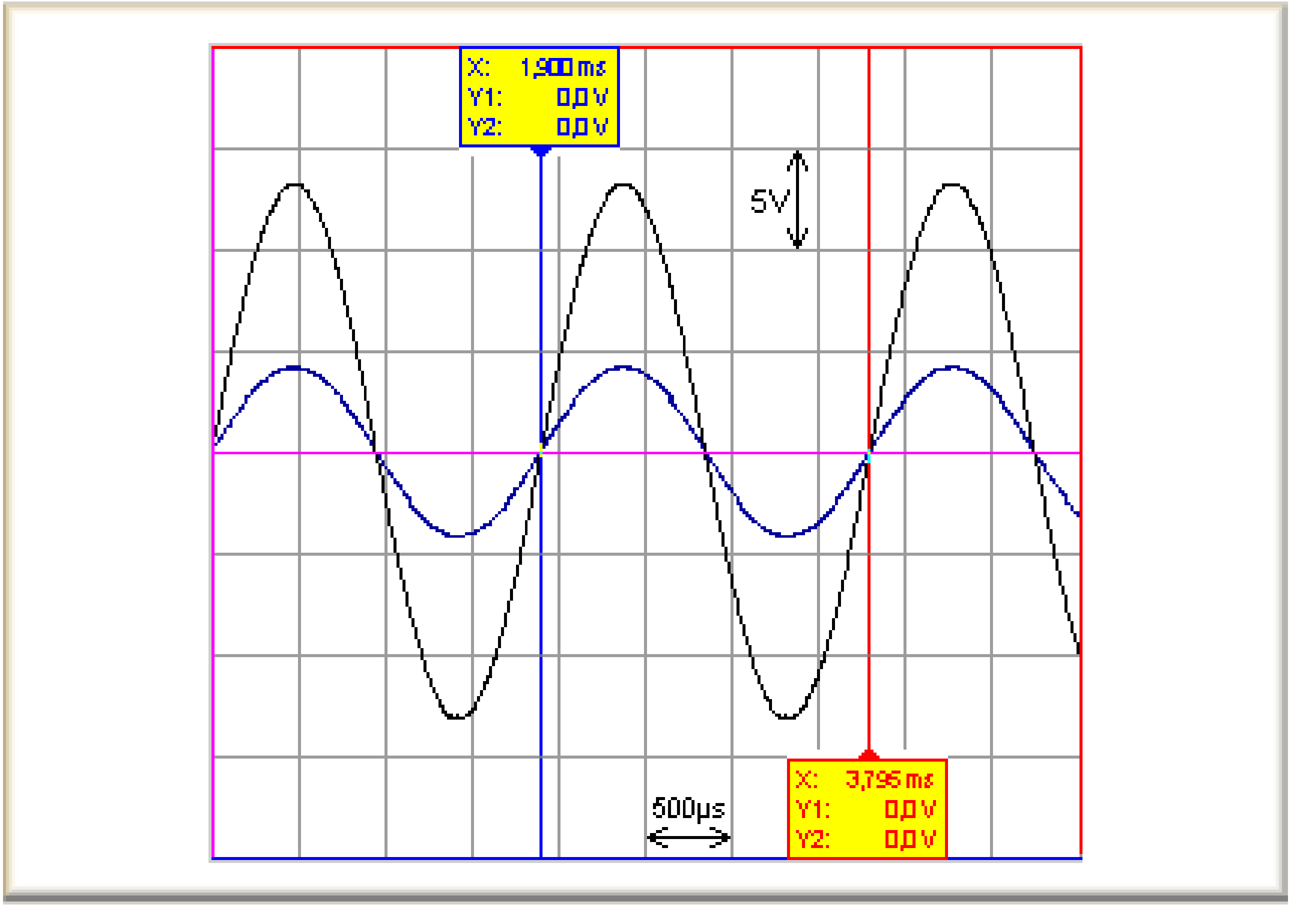
14.2 Circuit setup



The RC elements (R_1, C_1 and R_2, C_2) of the Wien bridge determine the positive feedback and thus the frequency of the oscillation. R_3, R_4 and R_5 form a voltage divider. They determine the negative feedback and thus the course (the amplitude) of the oscillation. If the negative feedback is too strong, the oscillation stops. If the negative feedback is too weak, the positive feedback predominates and the OPA is overloaded.

With potentiometer R_3 a sinusoidal shape can be adjusted.

14.3 Evaluation



The frequency of the signal is approximately 500 Hz.

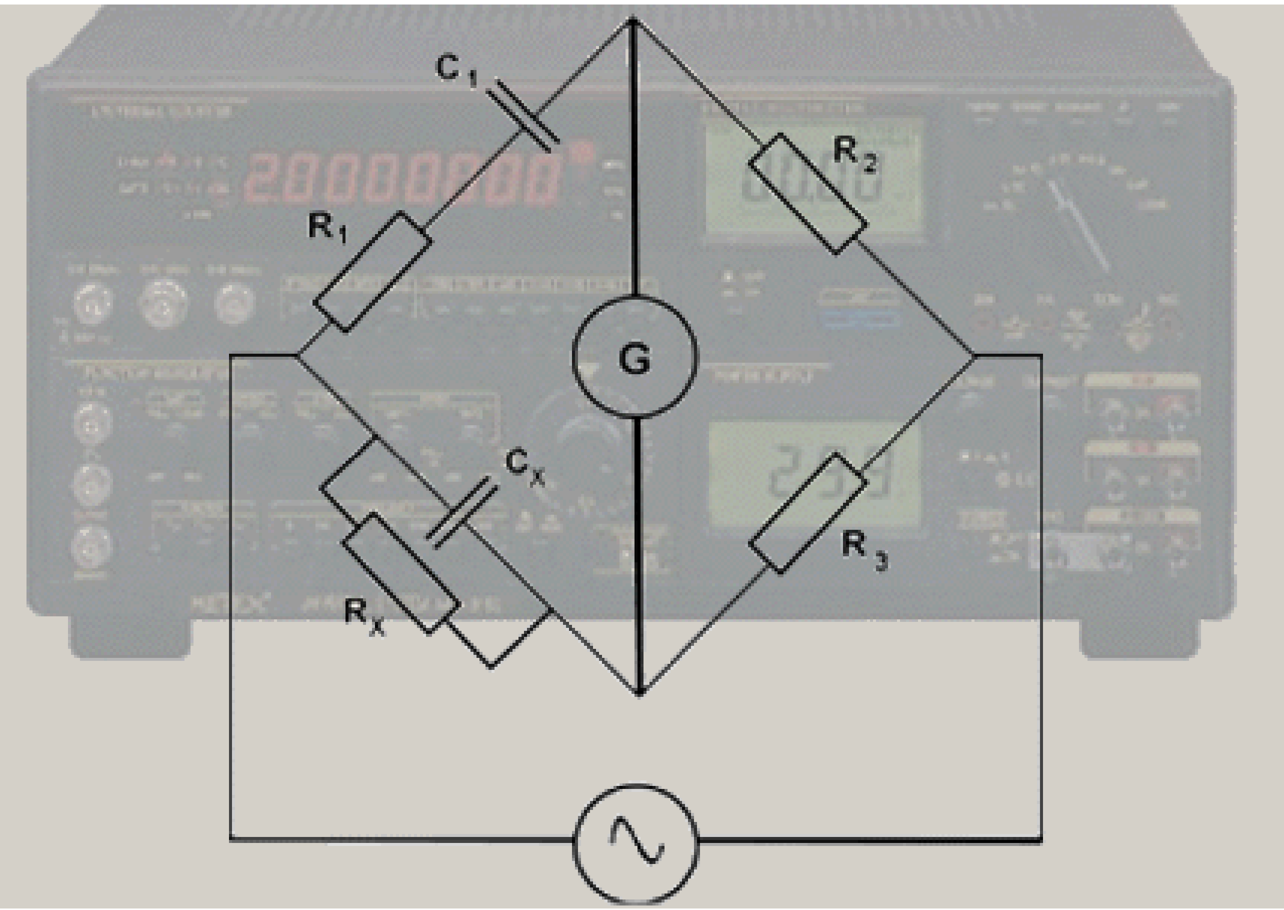
The system is sensitive to small changes at the Wien bridge[1] , such as connection of an oscilloscope or touching with a finger (the frequency and damping of the bridge are detuned).

The output signal and the potential at the non-inverting input are in phase (condition for the system's oscillation).

[1] **Changes at the Wien Bridge**

When a scope is connected, the change in the ohmic resistance predominates compared with the additional capacitance. The total resistance of the Wien bridge therefore becomes smaller so that the time constant decreases and the resonance frequency increases. On touching with a finger, the capacitive change predominates. The total capacitance increases leading to a higher time constant and a lower resonance frequency.

14.4 Application

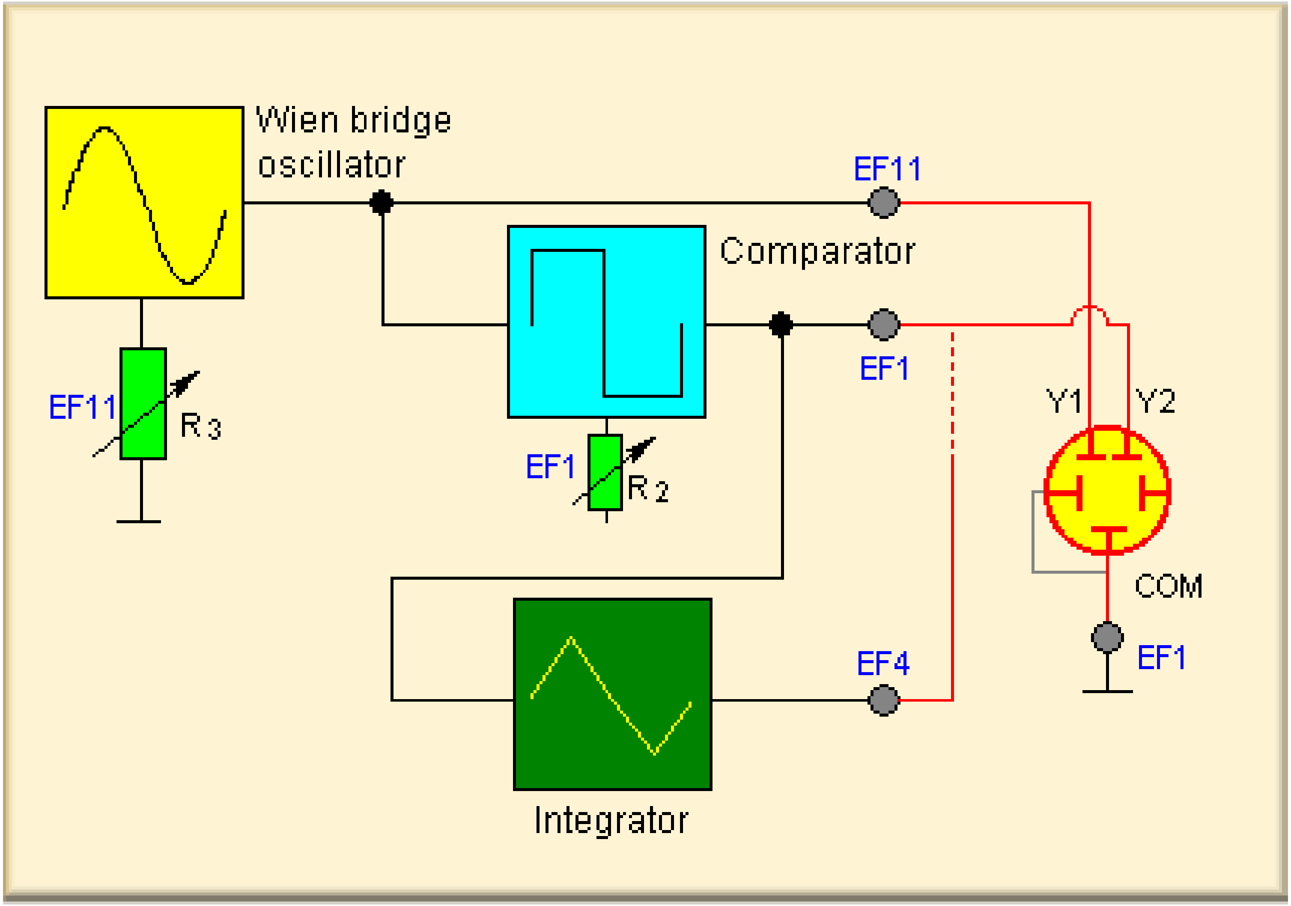


Wien bridge oscillators are employed in analog function generators for generating low-frequency sinusoidal signals. They belong to the RC oscillators and are used in the frequency range from 0.1 Hz up to about 100 Hz.

15.1 Introduction

A function generator for various output signal consists of a frequency generating element and several elements that determine the shape of the signal. The most common signal shapes are the **sinusoidal**, the **delta** and the **rectangular** signal.

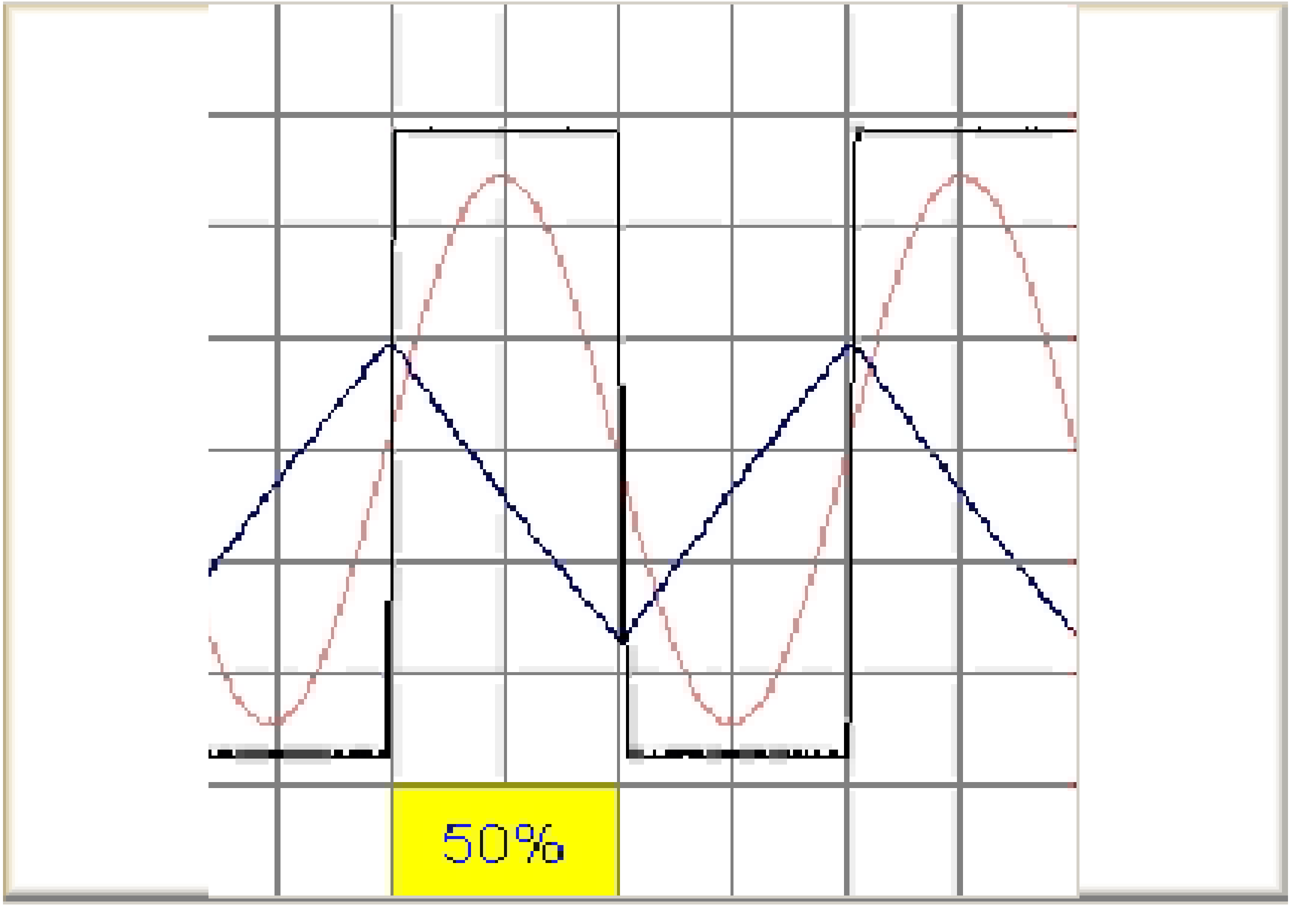
15.2 Circuit setup



In our case, the frequency determining element is a Wien bridge (adjustment with R_3 in EF11). With the comparator a rectangular signal is generated from the sinusoidal signal. The duty cycle of the rectangular signal is adjusted with R_2 in EF1.

The integrator converts the rectangular signal into a delta signal. Click the symbols in the block diagram to see the corresponding circuit diagrams.

15.3 Result

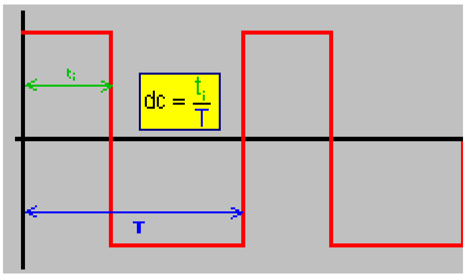


In the animation the signals are shown altogether. The percentage given is the duty cycle[1] of the rectangular function. A symmetric rectangular signal would be free of d.c. components for a duty cycle of 50 %

Due to the asymmetric limits of the OPA's dynamic range, the rectangular signal is not symmetric, and the signal is free of d.c. components at a duty cycle other than 50 %. A d.c. component is weighted with a gain of approx. –4.5 by the integrator realised in this experiment (see also the experiment "Integrator").

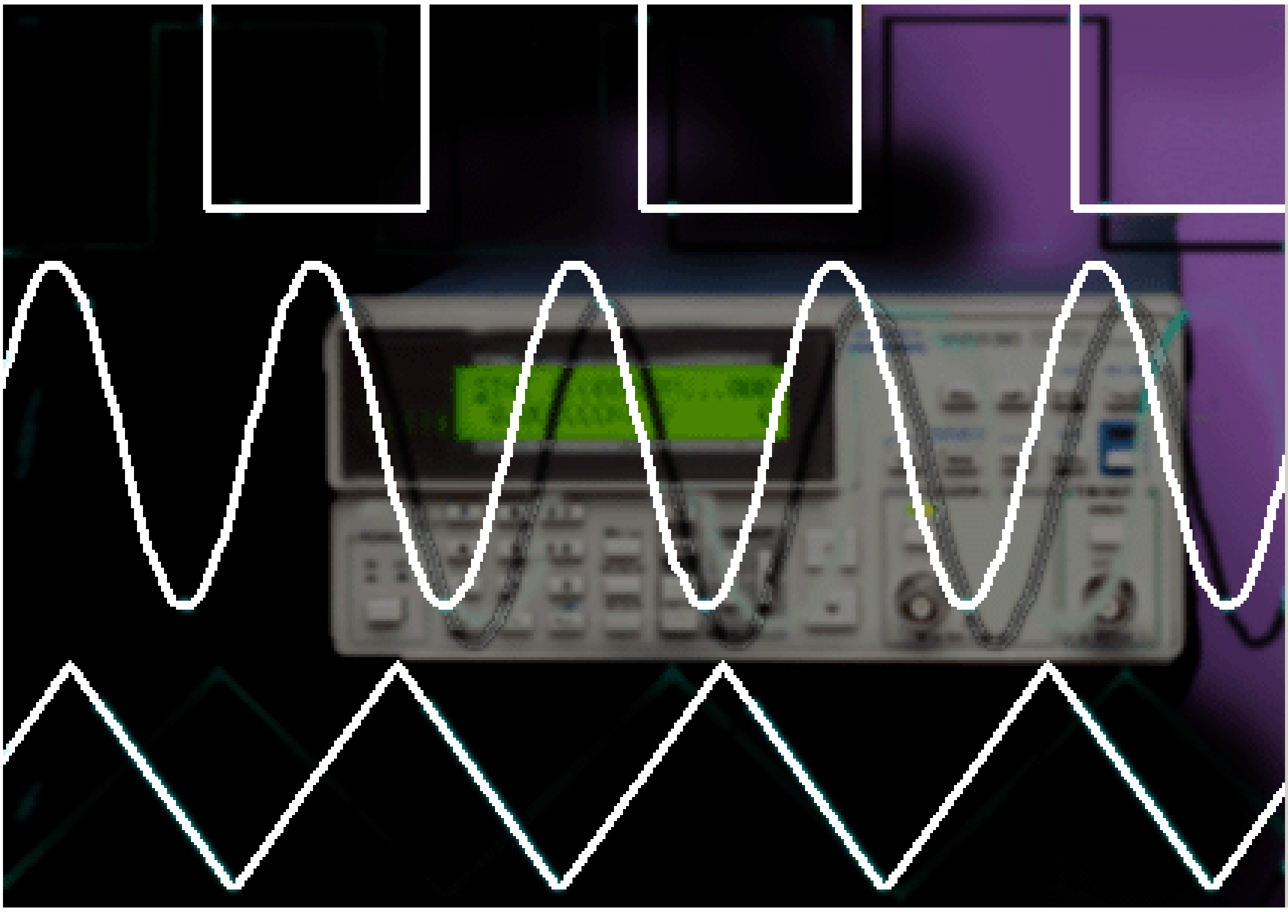
[1] **Duty Cycle**

The duty cycle of a periodic rectangular signal is the percentage of the period during which the signal has positive values.



In this example the duty cycle is dc = 0.4 = 40 %.

15.4 Application



Analog function generators provide high-quality signals. However, they are very difficult to adjust accurately, and the number of signal shapes depends on the number of elements used. By contrast, the signal shape of digital function generators such as the one used in COM3LAB depends only on the digital information. However, smoothing the signals is difficult because steps occur in the process of digital-analog conversion.

15.5 The end

That was the COM3LAB Course! We hope you enjoyed working out this CBT. We would be glad to hear your remarks, ideas and praise just as we welcome your suggestions for improvement, any mistakes you may have found, or other criticism! The fastest way is to send an e-mail to COM3LAB@ld-didactic.de[1]. Your LD Didactic Team is signing off now and we wish you much continued success in your future studies!

[1] mailto:COM3LAB@ld-didactic.de

1 Comparator

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7 Integrator

8 Differentiator

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12 Schmitt trigger

13 Astable multivibrator

14 Wien bridge oscillator

15 Function generator