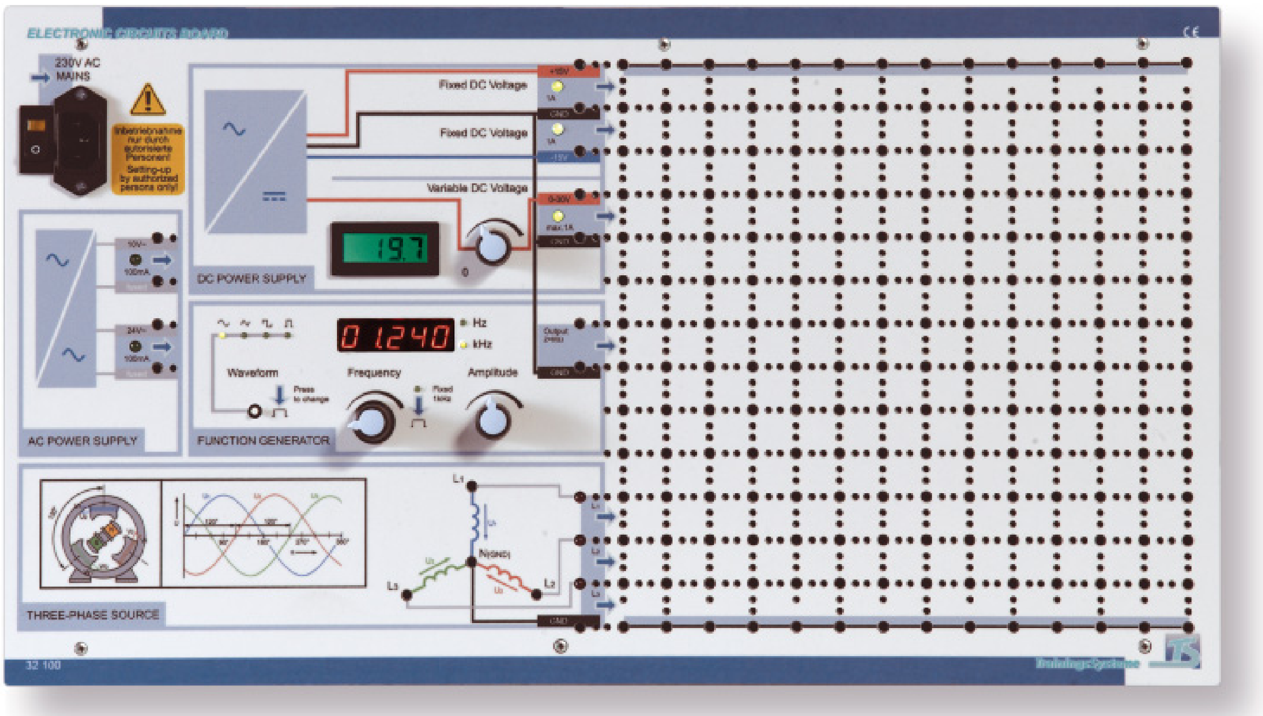
DC and AC Technology



Practical Experiments

Version 4.2 – Order No. E32 104

Safety Notice

Caution!

When assembling and testing the equipment, remember to observe all the necessary safety requirements, the laboratory regulations and all protective measures!

Do not apply any voltage until all connections have been completed and checked

Use only safety-protected test leads when assembling the exercise!

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Contents

1. The Electric Circuit

1.1 Components and Function of an Electric Circuit

When both poles of a voltage source are connected to the two terminals of a consumer, a current flows through the consumer. Thus, an electric circuit always contains at least three components:

- Voltage source: This contains the energy or charge, that drives the current through the circuit.
- Consumer: Depending on the type of consumer, the flow of current causes the desired effect, i.e. light, heat, sound, electromechanical movement, etc.

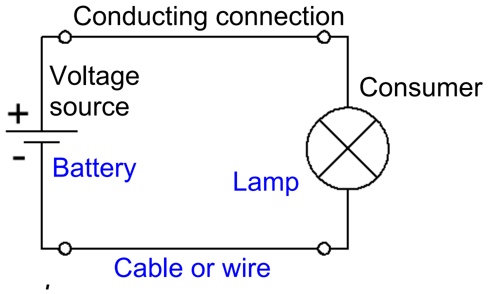


Fig. 1.1.1: The electric circuit

- Conducting connections: They have the task of allowing a flow of current between source and consumer. The connections can be in the form of wires, copper tracks on a printed circuit board or other conducting material.

A **current** is described as the movement or flow, of an electric charge through a conducting material to effect an exchange of charge. The flow of current between the poles of a voltage source, is caused by the opposing charges present at the terminals of the source. Current can only flow in a closed electric circuit.

- The **negative pole** of a voltage source has a **surplus of electrons**, this produces a **negative charge**.
- At the **plus pole** of a voltage source there is a **deficiency of electrons**. This produces a **positive charge**.

The direction of current flow is specified when describing the function of a circuit. There are two different definitions that are used:

- For **technical purposes, the direction of current flow** is assumed to be from the plus pole of the voltage source through the circuit connected, to the negative pole; i.e. external to the voltage source.
- The **physical direction of current flow** is from the negative pole to the plus pole of the voltage source.

Note: If not otherwise mentioned, the technical direction of current flow will be used in this handbook.

The reason for the flow of current, is that the charges are attempting to equalise each other. This is known as electric voltage. It can be measured, using suitable instruments connected across the poles of a voltage source. The magnitude of the voltage is a measure of the charge quantity. An electric voltage can also be measured when there is no flow of current.

The magnitude of the current flowing in a closed circuit, depends in part, on the magnitude of the voltage applied. The current flow is also determined by the consumer, since the consumer presents an electrical **resistance** that opposes the flow of current.

1.2 Description of Basic Electrical Quantities

The previously defined basic electrical quantities, Current / Voltage / Resistance, have a direct relationship and can be described, mathematically:

Current: The magnitude of current flowing (**I**) in a circuit corresponds to the quantity of charge (**Q**), that flows per unit of time (**t**) through a conducting medium. Formula:

$$I = \frac{Q}{t}$$

Voltage: The quantity of charge present in a voltage source determines its energy content (**E**) and the voltage present at the poles (**U**). Formula:

$$U = \frac{E}{Q}$$

Resistance: The current is driven by the voltage and restricted or limited by the sum of all resistances (**R**) in the circuit. The formulae shown here apply:

$$I = \frac{U}{R} \quad \Rightarrow \quad R = \frac{U}{I}$$

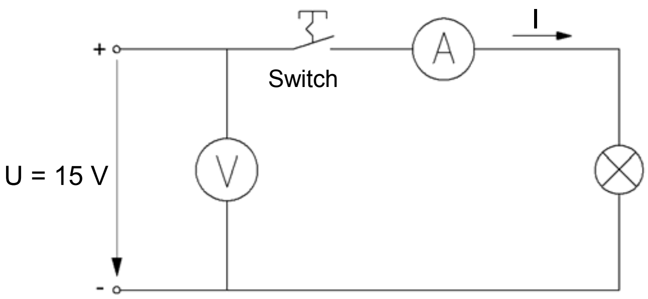
Table 1.2.1 summarises the basic electrical quantities, gives the units and standard abbreviations.

	Formula character	**Basic unit**	**Unit character**	**Units commonly used**
Voltage	U	Volt	V	mV, V, kV
Current	I	Ampere	A	µA, mA, A
Resistance	R	Ohm	□	□, k□, M□
Charge	Q	Coulomb	C	mC, C

Table 1.2.1: Basic electrical quantities

1.3 The Electric Circuit in a Practical Exercise

To examine the basic electrical quantities in a circuit, test instruments are required that indicate the magnitudes of current and voltage. A so-called 'Multimeter' can measure both electrical quantities and can be used equally, as a 'Voltmeter' or 'Amperemeter' (commonly called an ammeter). The basic circuit in 1.1.1 is extended by the test instruments. Also, for an easy and safe closing and breaking the circuit, a switch is included (Fig. 1.3.1).



In Fig. 1.1.1 the voltage source was shown by the standard symbol for a battery. In the exercise, the DC voltage source from the Board is used. This provides a fixed voltage of 15 V or an adjustable voltage of 0 to approximately 30 V at the outputs (Fig. 1.5.2). This voltage is applied to the contacts of the circuit.

Fig. 1.3.1: Circuit with test instruments and switch

Exercise Sequence:

- **Set the main switch on the Electronic Circuits Board to OFF!**
- Assemble the exercise on the Board. Connect the outputs of the Fixed DC Voltage source (red socket '+15V' is the plus pole, black socket 'GND', is the negative pole) to the inputs of your circuit (Fig. 1.3.1).
- Now, switch the voltage supply to the Board ON.
- Check the basic functions of the circuit, by way of the lamp.

Switch to OFF: The lamp ....

Switch to ON: The lamp ....

- Measure the voltage between the inputs of the circuit with the multimeter and enter the values in table 1.3.2.

Switch	Voltage, U	Current, I	Lamp
Open			
Closed			

Table 1.3.2: Measured values

- Read the value of current at each switch setting and enter the values in table 1.3.2.

1.4 Tasks / Questions

- Which direction of current flow is shown in the circuit diagram in Fig. 1.3.1 and which direction in Fig. 1.4.1?

Circuit 1.3.1:

Circuit 1.4.1:

- What value is the current flow to the lamp, 'I_{to}' assumed to be in relation to the return current from the lamp 'I_{from}'?

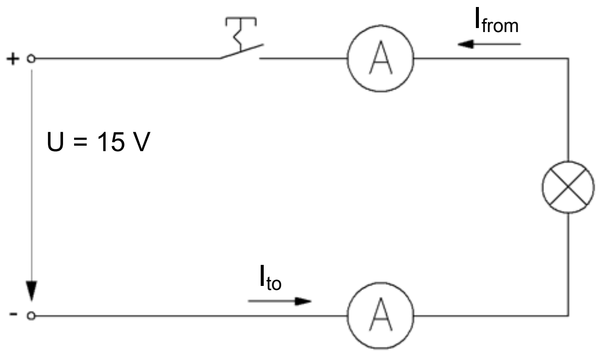


Fig. 1.4.1: Circuit for the first question

- Check your statement by measurement.

I_{to} =

I_{from} =

1.5 Test assembly on the Electronic Circuits Board

Construction of the circuit:

- **During construction (or any changes) of the circuit always ensure that the main switch 'MAINS' on the Electronic Circuits Board (left hand top corner on the Board) is set to OFF!**
- Note: The 2mm and 4mm sockets that are directly adjacent to each other, are connected together. Between any other neighbouring 2mm sockets there is no connection (see Fig. 1.5.1).
- First, the bridges should be inserted in the patchboard as 'conducting paths'. The positions marked 'Switch' and 'Lamp' remain free (see Fig. 1.5.2).

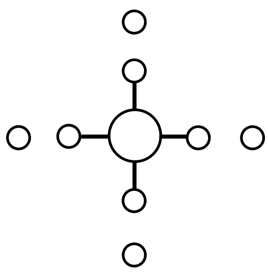


Fig. 1.5.1: Connections layout on the patchboard

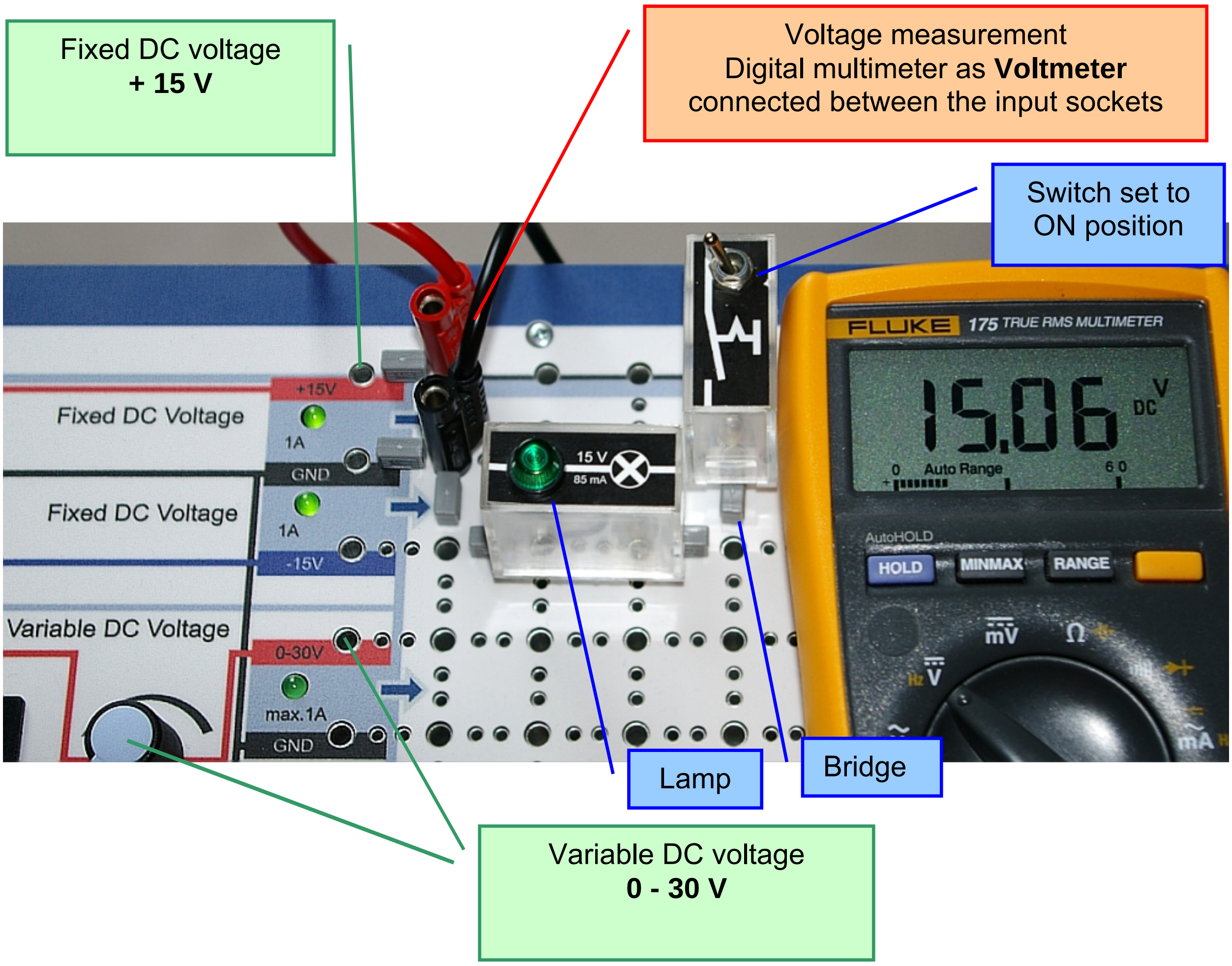


Fig. 1.5.2: Circuit construction and measurements on the Electronic Circuits Board

- Ensure that the circuit is connected to the outputs of the voltage source (plus pole: +15V / negative pole: GND) via bridging plugs (Fig. 1.5.2).
- Bridging plugs complete the circuit between the components lamp and switch (Fig. 1.5.2).

Measurement sequence:

- A **voltmeter** is always connected **in parallel** with the test points; **ammeters** must always be connected in the circuit, **in series** with the components (Figs. 1.3.1 and 1.5.2).
- The procedure for measurements with the multimeter depends largely on the type of instrument. Fig. 1.5.2 shows a voltage measurement with a digital multimeter. The voltmeter is connected to the input sockets of the circuit, using 4mm test leads.
- To measure the current flow, a bridging plug must be removed. An ammeter is inserted in its place.

2. Ohm's Law

2.1 Importance of Ohm's Law

As in discussed in chapter 1, the current flowing in a closed circuit, is dependent only on the applied voltage and the limiting effect of the resistance of the consumer. **Ohm's law** describes in mathematical form, this statement of the relationship between the basic electrical quantities voltage (U), current (I) and resistance (R) in a circuit.

Thus,

$$I = \frac{U}{R} \quad \Rightarrow \quad U = R \cdot I \quad \Rightarrow \quad R = \frac{U}{I}$$

A missing quantity can be calculated from the formulae above, when two other values are known.

- With a constant resistance R, the current flow increases as the applied voltage is increased. In other words, the current flow is **directly proportional** to the applied voltage.
- If on the other hand, the applied voltage U remains constant and the resistance R is varied, the current flow is **indirectly proportional** to the variation in resistance.

The German physicist Georg Simon Ohm noticed these effects and made public in 1826 his now famous, law. In his honour, the unit of electrical resistance was defined as 'ohm'.

2.2 Ohm's Law in a Practical Exercise

The exercises are completed with a circuit where various values of resistance R, are used. The standard circuit symbol for a resistor is a rectangle (Fig. 2.2.1). For measurements, the ammeter is connected in the circuit. The voltage driving the flow of current, is measured directly across the current-limiting resistor. **Note: The term 'resistor' is usually used to denote a component that introduces resistance into a circuit.**

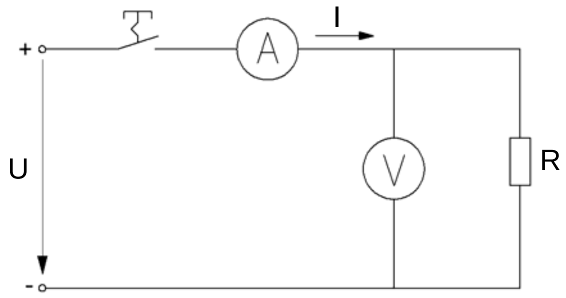


Fig. 2.2.1: Practical exercise for Ohm's law

- **Set the main switch on the Electronic Circuits Board to OFF!**
- Assemble the exercise on the Board (Fig. 2.2.1). Connect the outputs of the Variable DC Voltage source ('0 – 30 V' is the plus pole, 'GND' the negative pole) to the inputs of the circuit. As a resistance, first use the plug-in component R = 100 Ω.

2.2.1 Examining the Relationship between Current and Voltage

The first measurement examines the reaction of the current to changes in the voltage. Also expressed a “current as a function of voltage”. Mathematics expression: **I = f (U)**.

- Set the voltage values as given in table 2.2.1.1 one after the other (check each value on the voltmeter across the resistor). At each voltage, measure the value of current flow in the circuit and enter the values in the table.

U [Volt]	0	1	2	4,5	6,5	8,5	10
I [mA], R = 100 Ω							
I [mA], R = 220 Ω							

Table 2.2.1.1: I = f (U)

- Replace the resistor with one of R = 220 Ω. Repeat the series of measurements and complete table 2.2.1.1, accordingly. After completion, set the switches on the Board and circuit to OFF!
- Plot both series of measured values in the chart below (Fig. 2.2.1.2) and join the points plotted to produce a characteristic for each resistor.

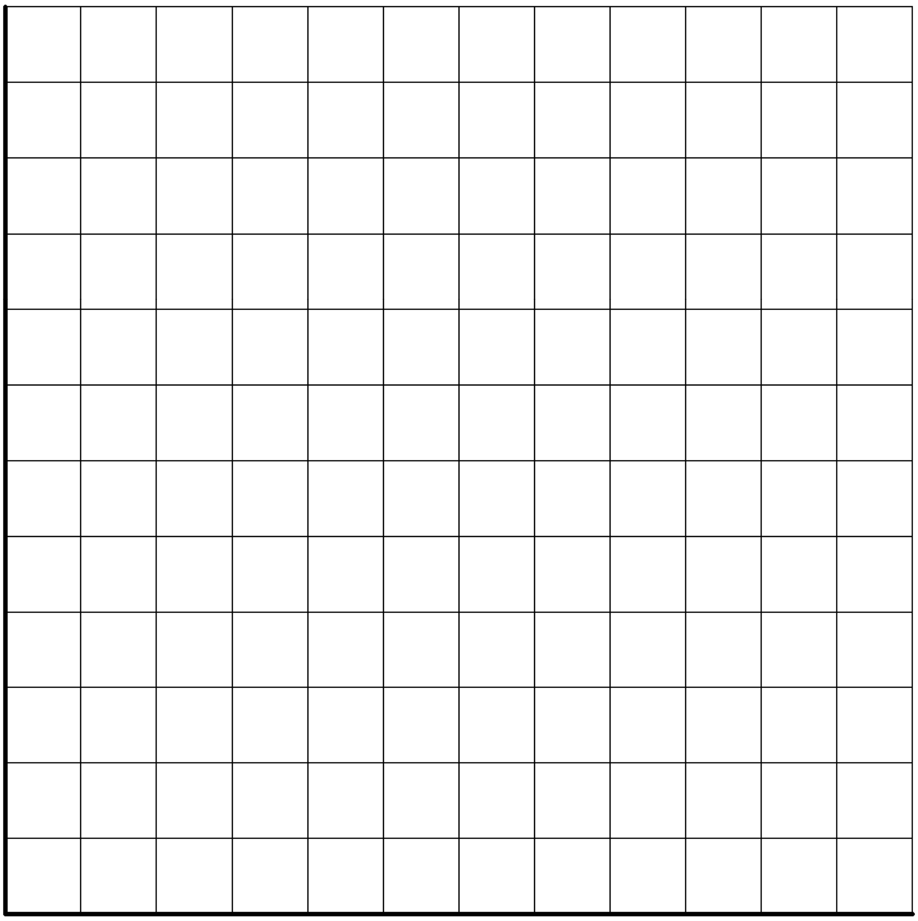


Fig. 2.2.1.2: Graph I = f (U)

2.2.2 Examining the Relationship between Current and Resistance

In this exercise, the current flow is measured for different values of resistance. The voltage remains constant and is thus, “current as a function of resistance”. Mathematics expression: I = f (R) .

- Have the resistors given in table 2.2.2 ready to hand and first insert a resistor with a value of R = 33 Ω in the measurement circuit (Fig. 2.2.1).
- Set the voltage across the resistor to 4 V. Measure the current in the circuit and enter the value in table 2.2.2.1.
- Complete the series of measurements and note the current each time, in the table.

R [Ω]	33	100	330	470	680	1000
I [mA], U = 4 V						
I [mA], U = 7 V	XXXX					

Table 2.2.2.1: I = f (R)

- Increase the voltage to 7 V and repeat the series of measurements (**Not R = 33 Ω!**). Enter the values measured in table 2.2.2.1.
- Plot the values from the table in the chart given here (Fig. 2.2.2.2).
- Draw the characteristics I = f (R) for both voltages.

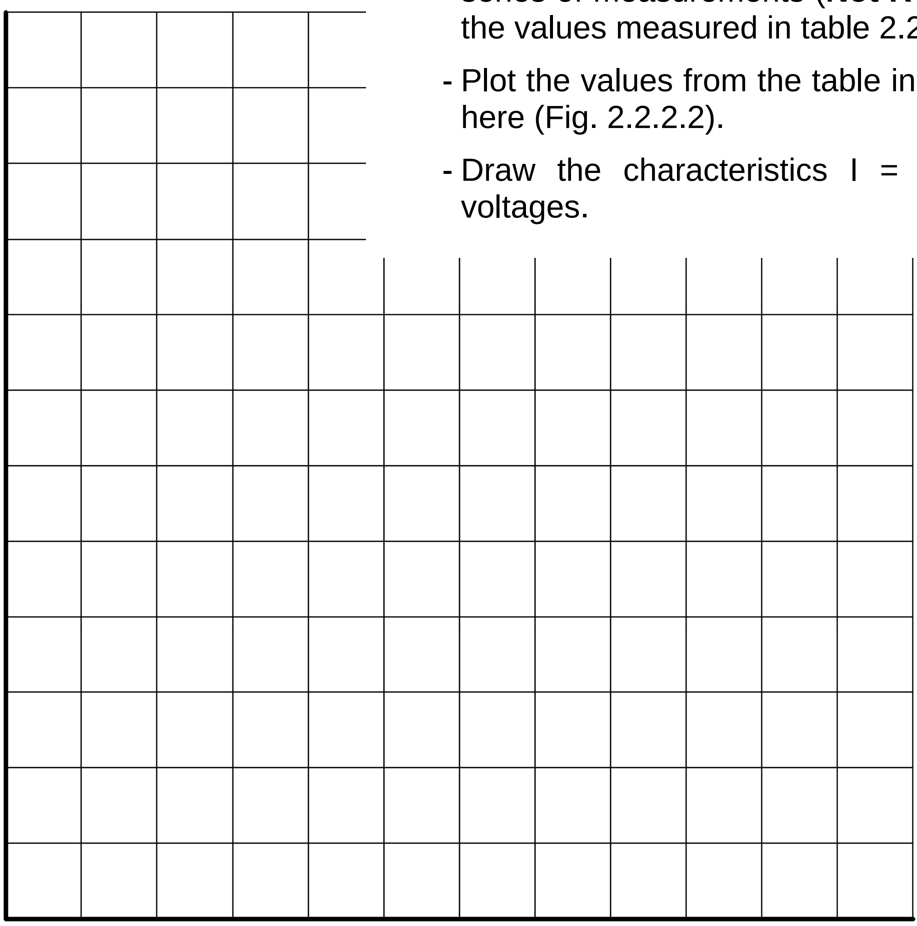


Fig. 2.2.2.2: Diagram I = f (R)

2.3 Tasks / Questions

- Calculate the current I, flowing through the resistor R, shown in Fig. 2.3.1, when the switch is closed.

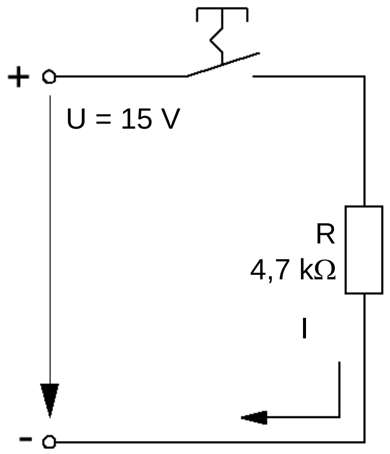


Fig. 2.3.1: Task for Ohm's law

- Check your calculation by measurement.

  Measured value:

- How does the current change when the voltage is descreased?

- The resistor is replaced by a component with a smaller resistance. The voltage remains unchanged. How does the current in the circuit react?

- The voltage across the resistor is doubled, R remains constant. What is the value of current flow now?

- The voltage U in Fig. 2.3.1 assumes the value 2,18 V. What value of resistor R must be used for the current to remain unchanged at 3,2 mA? Calculate the value of resistance and check your calculation by measurement.

  Calculated:

  Measurement check:

2.4 Exercise Assembly on the Electronic Circuits Board

Fig. 2.4.1 shows a possible test assembly for all exercises in chapter 2 “Ohm's Law”.

Warning:
Current flowing through a resistor produces heat. Thus for example, the components inserted in Fig. 2.4.1 have a rating limit of 2 Watt.

Never connect a higher value of voltage to the exercise circuit than those specified!

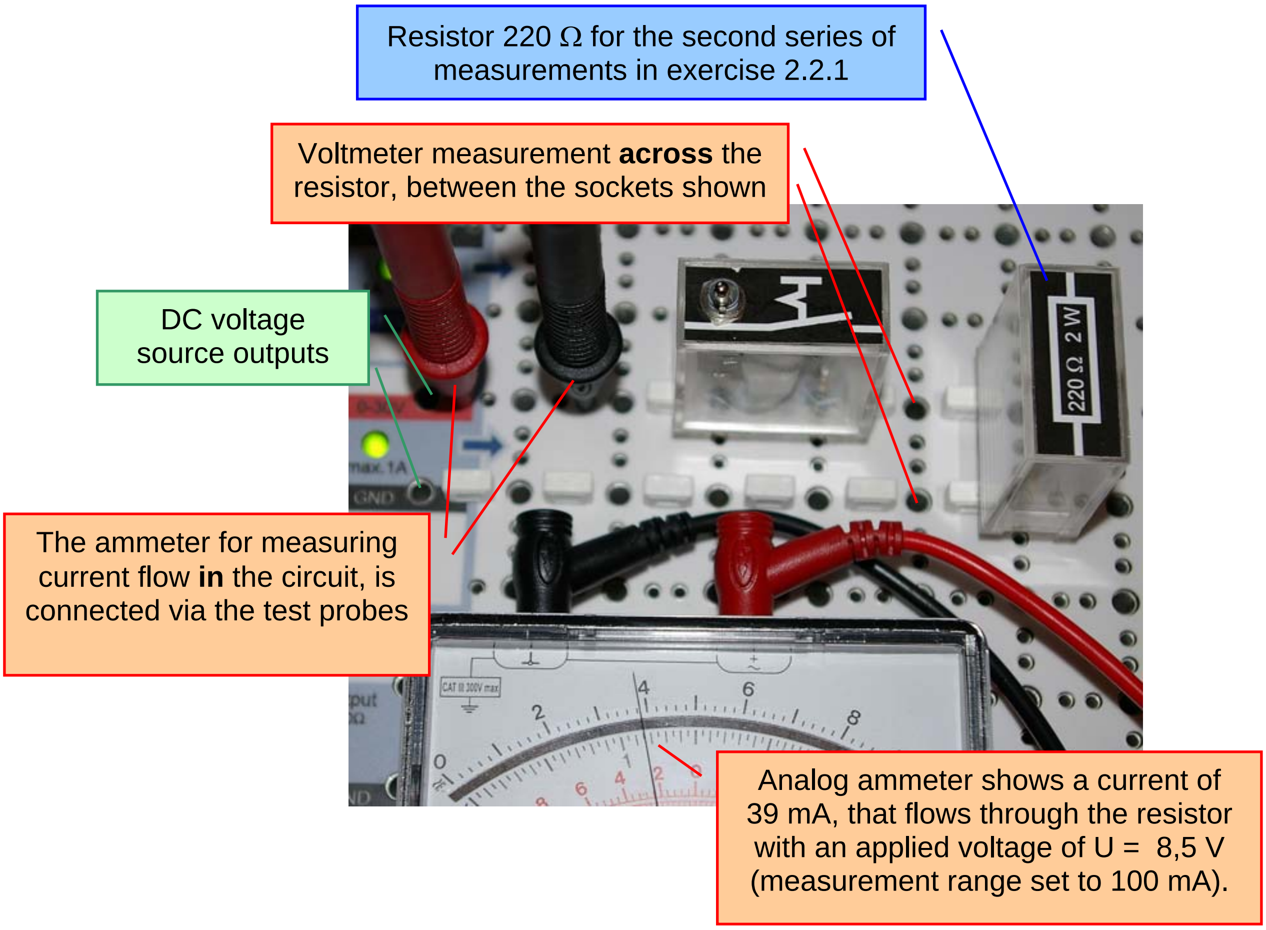


Fig. 2.4.1: Test assembly for the exercises on “Ohm's law”

3. Electrical Resistance

3.1 Types and Properties of Electrical Resistance

Electrical resistance has the property of limiting the magnitude of current flowing in a circuit. In principle, any form of resistance is a consumer that absorbs energy from the circuit and radiate this energy in the form of heat into the environment. Resistances with special functions (lamps, signal sensing elements, motors, etc.), convert the electrical energy into other physical forms of energy.

In this conversion process, a certain amount of work or power (P), is effective at the resistance that is proportional to the current flowing through the resistance and the applied voltage.

The electrical power transformed at the resistance is given by: $\boldsymbol{P = U \cdot I}$

Quite often, either the current I, or voltage U, at the resistance is unknown. By substituting the unknown quantity by the application of Ohm's law, various forms of the expression for power, P, are obtained:

Substituting current: $P = U \cdot I$ *and* $I = \frac{U}{R} \Rightarrow P = \frac{U}{R} \cdot U \Rightarrow \boldsymbol{P = \frac{U^2}{R}}$

Substituting voltage: $P = U \cdot I$ *and* $U = R \cdot I \Rightarrow P = R \cdot I \cdot I \Rightarrow \boldsymbol{P = I^2 \cdot R}$

Electrical power is given with the unit Watt, W.

The **rating** must be known for any resistors used in electrical circuits. The rating indicates the maximum converted **power** that can be **dissipated** at the resistor without causing any damage to the component.

The rating of the resistors used with the Electronic Circuits Board can be read on the upper face of the plastic housing. Fig. 3.1.1 shows an example.

Fig. 3.1.1: Rating of the resistors in the accessory set for the Electronic Circuits Board

Resistors are temperature-dependent components. Their **temperature response** depends on the material used in manufacturing the resistor. The resistance of the component can increase or decrease as the temperature increases. This property is applied in the selection of resistors for specific purposes, where the change in resistance caused by variations in temperature is either positive or negative.

Calculation of the change of resistance, ΔR: $\boldsymbol{\Delta R = R_{20} \cdot \alpha \cdot \Delta \vartheta}$

where, : ΔR : Change in resistance
R_{20} : Resistance value at 20°C
α : Temperature coefficient of the material
$\Delta \vartheta$: Change in temperature

Resistors are the most frequently used components in electrical circuits. Product developer use resistors for setting voltage or current conditions in various sections of a circuit. Resistance also occurs where it is not wanted. An example, is the very small resistance of wires or conducting tracks on a printed circuit board (PCB), that oppose the flow of current. For practical purposes, in electronic circuits, this form of resistance can usually be ignored. With energy or signal transmission (up to a few kilometres), such losses do play a significant role. The resistance of a line is given by the length of line l, the cross-section of the line A and a material constant ρ (Greek letter 'rho'), known as the specific resistance:

$$R_{Line} = \frac{\rho \cdot l}{A} \quad \left| \begin{array}{ll} \rho & [\Omega mm^2/m] \\ l & [mm] \\ A & [mm^2] \end{array} \right.$$

A differentiation is made in the resistors manufactured for use in circuits, between **linear** and **non-linear** types of resistor. The value of linear resistors remains unchanged when the small effects of temperature are ignored. Thus, the current flow depends entirely on the applied voltage.

The value of non-linear resistors reacts to physical variables such as temperature, voltage or light. Here, depending on the applied voltage, they have a desired effect on the current flow.

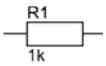
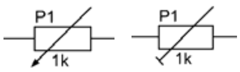
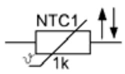
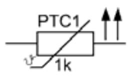
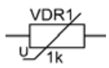
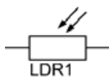
	Property	Description	Symbol
Linear	Fixed value	Resistor	
	Variable	Potentiometer, Trimmer	
Non-linear	Temperature dependent	NTC thermistor	
		PTC thermistor	
	Voltage dependent	Varistor	
	Light sensitive	Photoresistor (LDR)	

Table 3.1.2: Linear and non-linear resistors

Note: NTC = negative temperature coefficient
PTC = positive temperature coefficient
LDR = light dependent resistor

3.2 Linear Resistors

3.2.1 Properties of Linear Resistors

Resistors are considered to be linear when the current flowing through the resistor is dependent only on the applied voltage. The slight influence of temperature in this sense, is ignored. When the relationship between current and voltage is examined [I = f(U)], then a straight line (linear) characteristic is produced. The current is proportional to the applied voltage (also refer to section 2.2.1).

Industrially produced resistors always exhibit a deviation between the stated and actual, values. The maximum deviation is quoted as a percentage, either as a numerical value or as a colour code on the resistor.

3.2.2 Recording the Characteristic I = f (U)

- **Set the main switch on the Electronic Circuits Board to OFF!**
- Assemble the exercise on the Board (Fig. 3.2.2.1). Connect the outputs of the Variable DC Voltage to the inputs of your circuit. When connecting the test instruments, pay attention to the correct polarity. First, insert the plug-in resistor R = 1 kΩ.

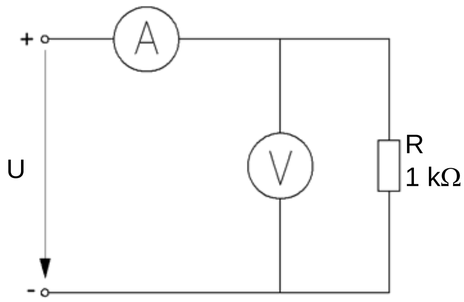


Fig. 3.2.2.1: Recording the characteristic I = f (U)

- For recording the characteristic, set the voltage values as shown in table 3.2.2.2 below and at each setting, measure the current flow through the resistor. Enter the values measured in the table.

	U [Volt]	**1**	**2**	**3,5**	**5,5**	**8**	**10**
R = 1 kΩ	**I [mA],**						
	P [mW]						
	R [kΩ]						
R = 4,7 kΩ	**I [mA],**						
	P [mW]						
	R [kΩ]						

Table 3.2.2.2: Recording the characteristic I = f (U)

- Plot the values measured for the first resistor in the chart (Fig. 3.2.2.3) and draw the characteristic of the resistor, R = 1 kΩ.

- Repeat the series of measurements with the resistor R = 4,7 kΩ. Complete table 3.2.2.2, accordingly.
- Plot the values measured for the second resistor in the chart (Fig. 3.2.2.3) and draw the characteristic, I = f (U).

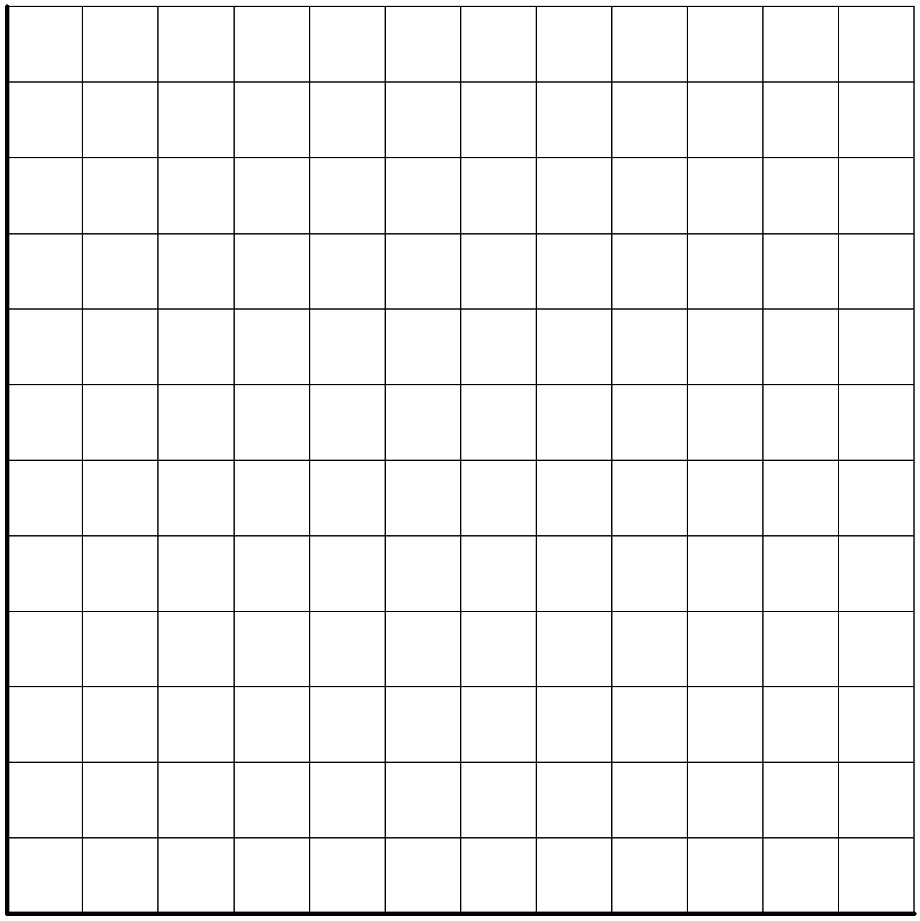


Fig. 3.2.2.3: Characteristics I = f (U)

- Using your measured values, calculate the power P, converted to heat for both resistors. Enter the calculated values in table 3.2.2.2.

  Formula to use:

- Select three pairs of measured values for each of the resistors 1 kΩ and 4,7 kΩ and calculate the actual value of resistance. Enter the calculated values in table 3.2.2.2.

  Formula to use:

- Form the average value of the 3 calculated results.

R = 1 kΩ:

R = 4,7 kΩ:

Calculate the deviation of the actual value of resistance from the given value, as a percentage. Is the component within the stated tolerance?

R = 1 kΩ:

R = 4,7 kΩ:

- The power converted at the resistor, increases as the voltage across the resistor is increased.
  The maximum output from the voltage source used here, is approximately 30 V. Calculate for both resistors, whether they can be overloaded when a high voltage is applied.

3.3 The NTC Resistor

3.3.1 Properties of an NTC Resistor

NTC = Negative Temperature Coefficient

Sometimes referred to as a Thermistor (not in common use today).

Resistors with a negative temperature coefficient (NTC) are manufactured so that their resistance value reduces as the temperature is increased. They conduct better when the resistor is warm. Heating or cooling of the resistor material depends on the ambient temperature and heat produced as a result of the current flow is converted by the resistor itself, and dissipated as warmth to the surrounding air.

Due to the temperature dependence of the resistor, the characteristic I = f (U) is not linear. It follows an approximate exponential curve, depending on the resistance material.

3.3.2 Recording the NTC Characteristics I = f (U) and R = f (U)

The response of an NTC resistor will now be examined. The change in temperature required is produced by the current flowing through the resistor. Of course, the existing temperature of the room will also have an effect on the exercise. This effect is ignored when evaluating the exercise.

- Assemble the exercise circuit on the Board (Fig. 3.3.2.1).

Note: The 220 Ω resistor is used for current limiting, a protection resistor for the NTC resistor. The effect of this resistor in the circuit can be ignored.

- For recording the characteristics, set the voltage values as shown in table 3.3.2.2, in sequence commencing with 5 V.
- After setting each voltage, wait a few minutes until the current flow has stabilised. Then, measure the current and enter the values measured in table 3.3.2.2.

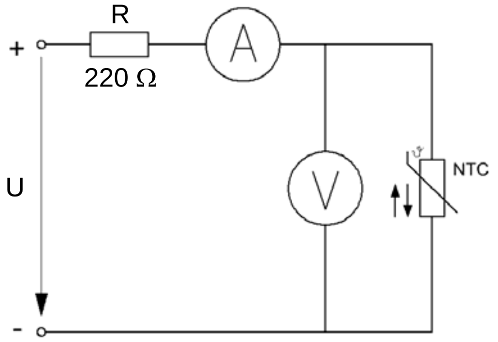


Fig. 3.3.2.1 : Characteristic recording I = f (U) and R = f (U)

- **NOTE: Depending on the temperature of the room, your results can differ slightly from those given in the table. With voltages higher than 20 V, the effect of the protection resistor is too great.**

U [V]	5	10	15	17	19	20
I [mA]						
R_{NTC} [kΩ]						

Table 3.3.2.2: Characteristics, I = f (U) and R = f (U) for the NTC resistor at room temperature

- From the values measured for U and I, calculate the values of the resistor and enter the values in the table 3.3.2.2.
- Plot the values of current measured in the chart (Fig. 3.3.2.3) and join the points to give the characteristic I = f (U).
- Also, plot the values of U and R in the chart (Fig. 3.3.2.3). The y-axis of the coordinates system is also used as a resistance scale.
- Join the points plotted to give the characteristic R = f (U).

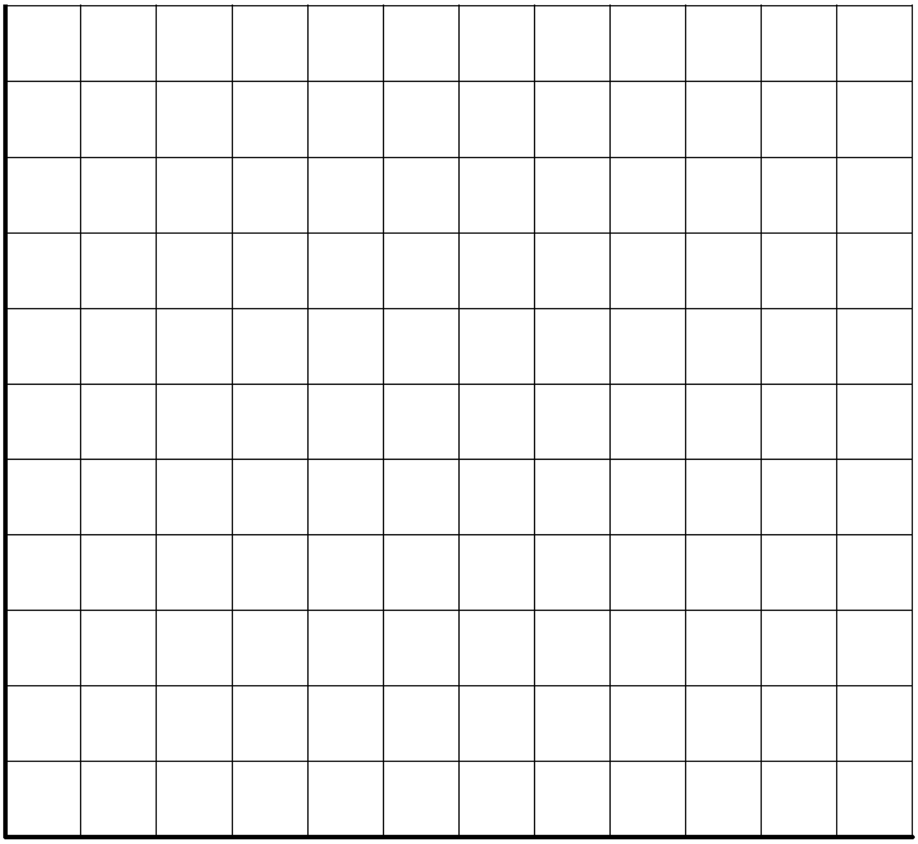


Fig. 3.3.2.3: Characteristics I = f (U) and R = f (U) for the NTC resistor at room temperature

- Break the circuit in Fig. 3.3.2.1 by removing a bridging connection. Set the voltage at the output of the source to 20 V. Select a suitable current range on your multimeter corresponding to the expected current flow.
- Now, close the circuit (insert the bridge again) whilst observing the indication on the ammeter. How does the flow of current respond at the instant of closing the circuit, and afterwards?

- Explain what is seen on the basis of the properties of an NTC resistor and reference to Ohm's law.

3.4 The PTC Resistor

3.4.1 Properties of a PTC Resistor

PTC = Positive Temperature Coefficient

Resistors with a positive temperature coefficient (PTC) are manufactured so that their resistance value increases as the temperature increases. They conduct better when the resistor is cold. Heating or cooling of the resistor material depends on the ambient temperature and heat produced as a result of the current flow is converted by the resistor itself, and dissipated as warmth to the surrounding air.

Due to the temperature dependence of the resistor, the characteristic I = f (U) is not linear.

3.4.2 Recording the PTC Characteristics I = f (U) and R = f (U)

The response of a PTC resistor will now be examined. The change in temperature required is produced by the current flowing through the resistor. The effect of room temperature on the exercise is ignored.

Metals have the property of increasing their resistance value when they are heated (see also section 3.1). The metallic filament in a lamp for producing light, uses this property and is thus similar to the response of a PTC resistor. For this reason, a lamp is used to replace a resistor when recording the characteristic.

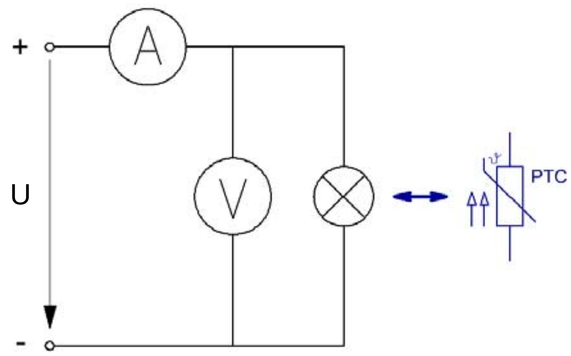


Fig. 3.4.2.1 : Characteristic recording I = f (U) and R = f (U)

- Assemble the exercise circuit on the Board (Fig. 3.4.2.1).
- For recording the characteristics, set the voltage values as shown in table 3.4.2.2, in sequence commencing with 0 V. At each voltage setting, measure the current and complete table 3.4.2.2.

NOTE: Depending on the temperature of the room, your results can differ slightly from those given in the table.

U [V]	0	1	5	10	15	20
I [mA]						
R_{PTC} [Ω]	ca. 50 (Room temperature)					

Table 3.4.2.2: Characteristics, I = f (U) und R = f (U) for the PTC resistor at room temperature

- From the values measured for U and I, calculate the values of lamp resistance. Complete table 3.4.2.2.
- Draw the characteristics I = f (U) and R = f (U) in the chart (Fig. 3.4.2.3).

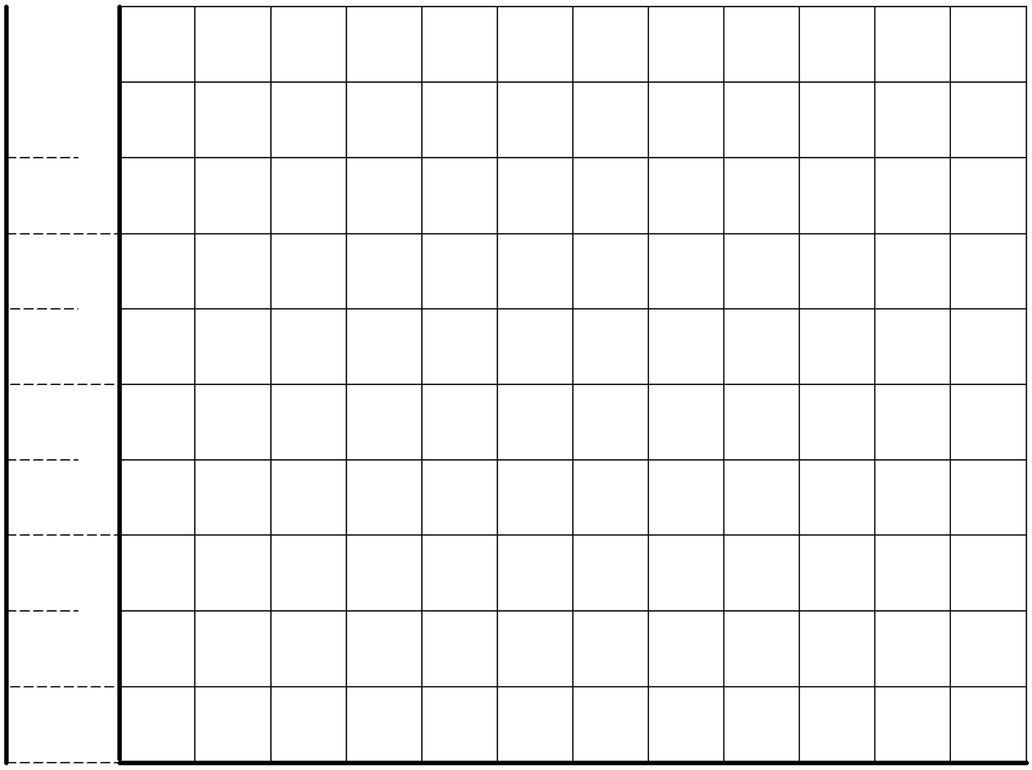


Fig. 3.4.2.3: Characteristics, I = f (U) and R = f (U) of the PTC resistor ('lamp')

- What current flows through the lamp at the instant of switching on, when the voltage across the lamp is 12 V? What conclusions can be drawn from the calculation result, with regard to the failure of filament lamps?

3.5 Voltage Dependent Resistor (VDR)

3.5.1 Properties of a VDR

Sometimes referred to, as a Varistor

The resistance of a voltage dependent resistor becomes smaller as the voltage across the resistor is increased. These components are often used in electronic circuits to compensate for unwanted increases in voltage. These changes in voltage can be in the form of slow changes in voltage level (e.g. for voltage stabilising). A VDR is also used for compensating fast transitions of voltage (e.g. spark suppression at contacts, over-voltage protection, etc.).

Because of its extreme dependence on voltage, the characteristic of a VDR I = f (U), is not linear.

3.5.2 Recording the VDR Characteristics I = f (U) and R = f (U)

The response of a VDR will now be examined.

- Assemble the exercise circuit on the Board (Fig. 3.5.2.1.)

Note: The resistor R = 1 kΩ is used for limiting the current, i.e. as protection resistor for the VDR. Its effect in the circuit is ignored.

- For recording the characteristics, set the voltage values as shown in table 3.5.2.2, in sequence commencing with 13 V.
- At each voltage setting, measure the current and complete table 3.5.2.2.

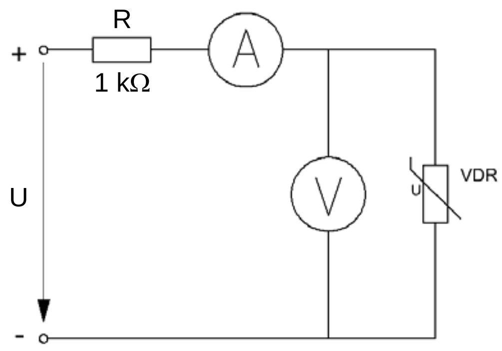


Fig. 3.5.2.1 : Characteristic recording I = f (U) and R = f (U)

NOTE: VDR's have large tolerance ratings, due to the methods of manufacture (up to 20 % of the nominal value). Thus, the values in the table are given only as guidelines and can differ from those obtained in your circuit.

U [V]	13	16	19	20	21	22
I [mA]						
R_{VDR} [kΩ]						

Table 3.5.2.2: Characteristics I = f (U) and R = f (U) at the VDR

- From the values measured for U and I, calculate the values of the resistance, R_{VDR}. Enter the calculated results in the table.
- Plot the values of current in the chart (Fig. 3.5.2.2) and draw the characteristic I = f (U) by joining the points plotted.

- Also, plot the values for U and R_{VDR} in the chart (Fig. 3.5.2.3) and draw the characteristic R = f (U) by joining the points plotted.

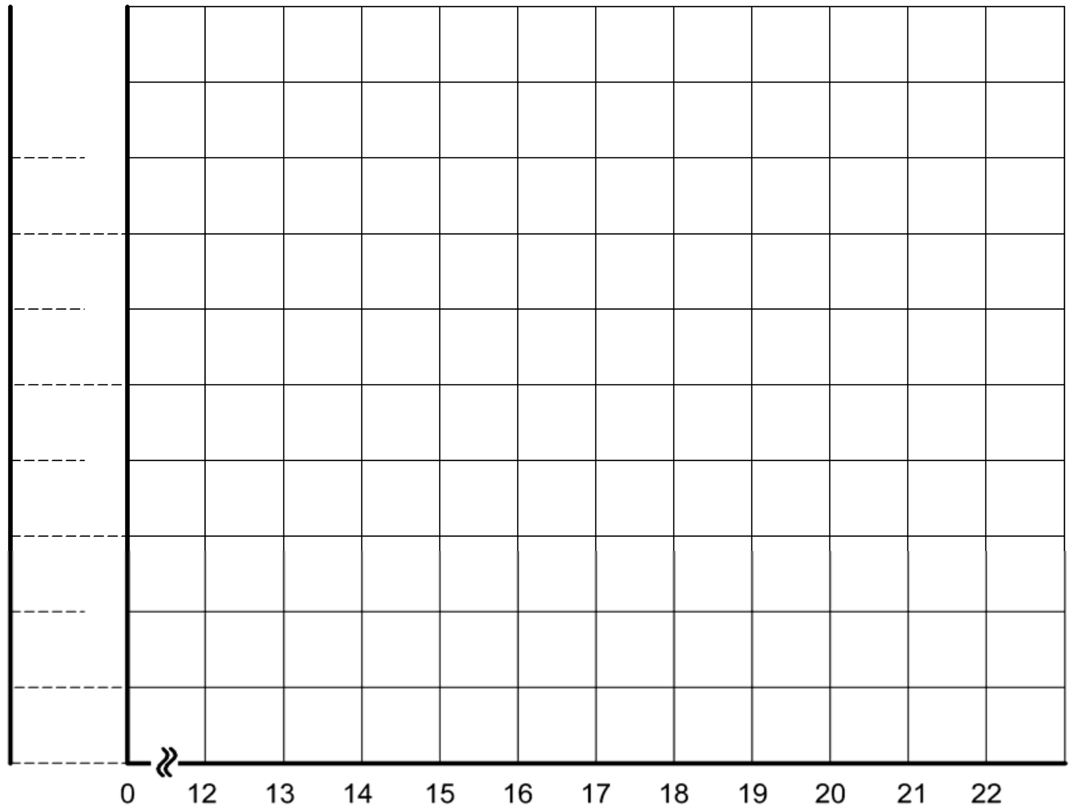


Fig. 3.5.2.3: Characteristics, I = f (U) and R = f (U) of the VDR

- By measurement and calculation, determine the power dissipation in the VDR at a voltage of 20,5 V.

U [V]	
I [mA]	

- Calculate the resistance value of the VDR at 20,5 V, using the value of power, P.

3.6 Photoresistor (LDR)

3.6.1 Properties of an LDR

LDR = Light Dependent Resistor

Commonly referred to, as an LDR

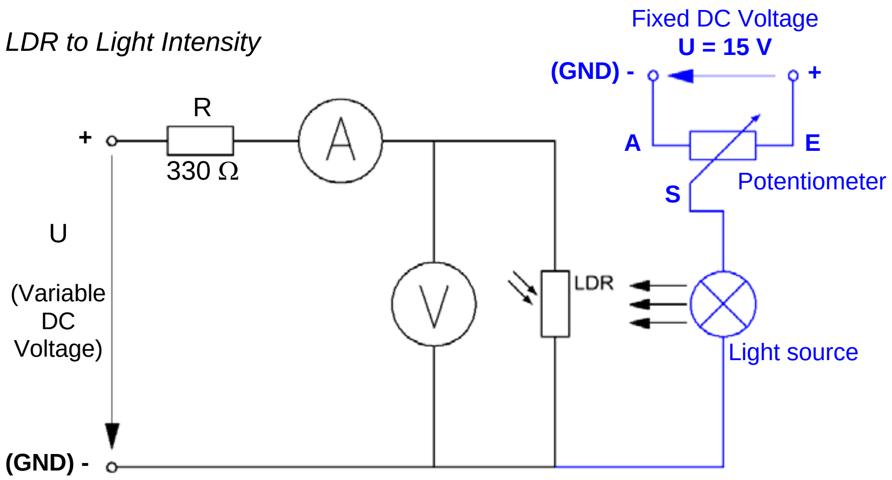
Photoresistors reduce in value when the intensity of incident light increases. They are used wherever a change in light intensity is to be detected and used as a signal in electronic circuits. For example, in light barriers, fire detectors, twilight switches, just to name a few.
A LDR is manufactured from special semiconductor material that when completely isolated from any light, has a resistance value in excess of 10 MΩ (so-called 'dark resistance'). When the component material absorbs light energy, charge carriers are released that produce a flow of current and thus, its conductance increases. A higher level of light energy increases the number of charge carriers released and the current flow is increased. At a maximum illumination, the resistance falls to the value of 'light resistance', in the region of approximately 100 Ω.

3.6.2 Examining the Response of the LDR to the Intensity of Light

The response of an LDR will now be examined to changes in the level of light intensity.

- Assemble the exercise circuit on the Board (Fig. 3.6.2.1).

Fig. 3.6.2.1: Response of the LDR to Light Intensity



Note: The circuit drawn in blue is used to produce a variable level of light intensity. A suggested layout for the plug-in components will be found in section 3.6.3.

- Connect the input (E) and output (A) of the potentiometer to the Fixed DC Voltage, U = 15 V.

Note: All negative poles on the voltage source, labelled 'GND' on the Board, should be connected together.

- Ensure that the LDR and light source are inserted, close to each other with the light-sensitive side of the LDR facing the light source to obtain optimum illumination. Also, the light source and LDR should be inserted away from the other components, so that the LDR and light can be covered during the exercise.

NOTE: The resistor R = 330 Ω is used as a protection resistor for the LDR. For the purposes of this exercise, its effect in the circuit is ignored..

- Set the potentiometer, for varying the DC voltage, to '0' (fully CCW).
- Switch the voltage supply on for the Boards and thus the Fixed DC Voltage and check that the intensity of the light source can be smoothly varied by way of the potentiometer.
- Then, set the potentiometer fully CCW (scale value '0').
- Cover the light and LDR (dark cloth, small box, or similar), to prevent as much stray light (or daylight), from influencing the exercise results.
- To begin the exercise, adjust the voltage across the LDR to U = 20 V (check on the multimeter). Since the LDR is dark (dark resistance >10 MΩ), there should be almost zero flow of current. Check this by measurement.

The scale values on the potentiometers (0…10), are given as a guide to the strength of illumination, in table 3.6.2.2.

Scale value	**0**	**2**	**3**	**4**	**6**	**8**	**10**
I [mA]							
U_{LDR} [U]							
R [kΩ]							

Table 3.6.2.2: Response of the LDR to Light Intensity

- Set the potentiometer to the scale values given in table 3.6.2.2. At each setting, measure the current and voltage at the LDR and enter the values in table 3.6.2.2.
- Calculate the resistance value of the LDR at the various levels of light intensity. Complete table 3.6.2.2 with your results of the calculations.
- What fundamental statements can be made from the values measured and the calculated resistance, with reference to the intensity of illumination?

- Can you identify an area of table 3.6.2.2, where a relatively small change in the intensity of illumination (scale value), produces a sudden change in resistance of the LDR from a high to a low value?

3.6.3 Exercise Assembly on the Electronic Circuits Board

Fig. 3.6.3.1 shows a possible layout of the plug-in components required, taking into account the cover required for the light sensitive LDR together with the light source. The light source used here, is an LED (light emitting diode). This component will be explained and examined, later. The voltage supply, and the intensity of illumination (sometimes referred to as 'luminosity'), is controlled by way of a potentiometer. This component is in effect, a variable resistance, which will be explained in a later section.

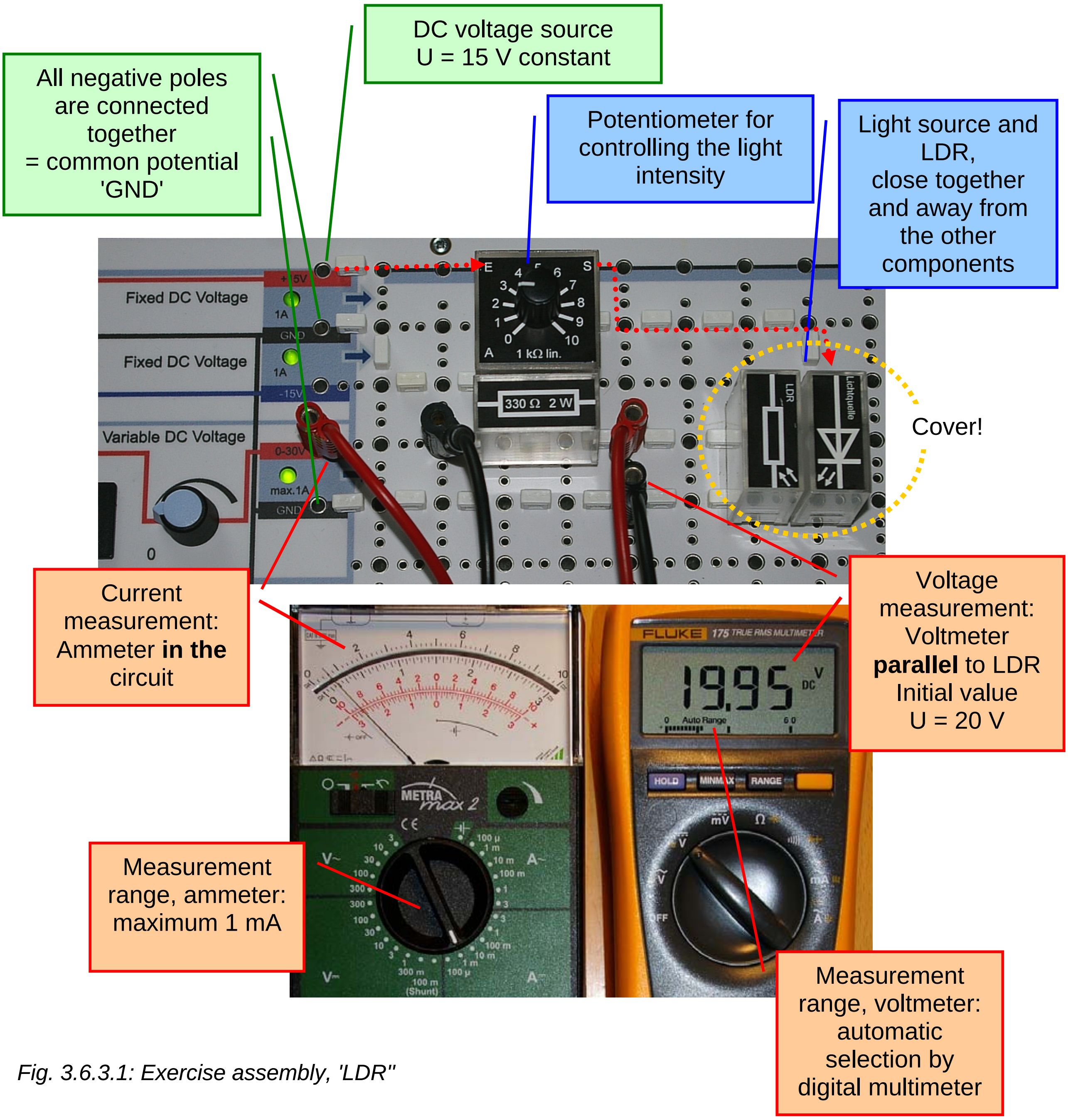


Fig. 3.6.3.1: Exercise assembly, 'LDR"

3.7 Series Connection of Resistors

3.7.1 Properties of a Series Circuit

If several resistors are connected in series between the plus and negative poles of a voltage source, then the **flow of current through all resistors is identical**.

Therefore, $I_{total} = I_{R1} = I_{R2} = I_{R3} = ... I_n$ applies.

A voltage can always be measured across a resistor through which a current is flowing. This is known as the 'voltage drop' across the resistor. The **sum** of all **voltage drops** across resistors R_1 to R_n in a series circuit, is equal to the **total voltage** U_{tot} present at the input to the circuit.

Formula: $U = U_{tot} + U_{R1} + U_{R2} + U_{R3} + ... + U_{Rn}$

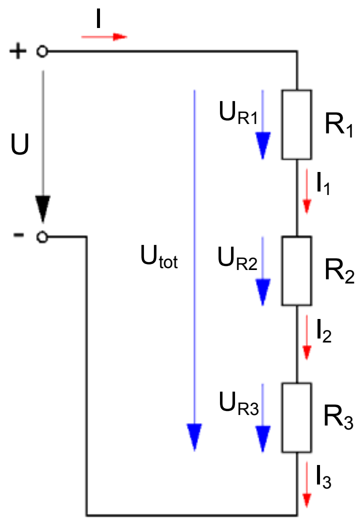


Fig. 3.7.1.1: Series circuit

An external voltage applied to a series circuit of resistors, is divided across the individual resistors. This is often referred to as a 'voltage divider', which is at the same time, an important task of resistors connected in series: 'Tap' a part of an applied voltage.

A series connection of resistors presents a total resistance in opposition to the current flow through the circuit, that can be calculated from Ohm's law:

$$R = \frac{U}{I}$$

After inserting the components of voltage:

$$R = \frac{U_1 + U_2 + U_3 + \ldots + U_n}{I}$$

Transforming:

$$R = \frac{U_1}{I} + \frac{U_2}{I} + \frac{U_3}{I} + \ldots + \frac{U_n}{I}$$

The quotient of partial voltage, U_n and total current I, corresponds to the associated resistor. Thus, the **total resistor is given by the sum of individual resistors.**

$$R = R_1 + R_2 + R_3 + \ldots + Rn$$

In Fig. 3.7.1.1, consider the arrow at the voltage input to the circuit, U and the arrows of the individual voltages, U_n. It can be seen that the voltages have opposite polarity (arrow points in opposition). Therefore, it can be said that the addition of all partial voltages in a closed circuit can be considered as '0'. This relationship is known as **'Kirchhoff's second law'**:

$$\sum U = 0 \quad \Leftrightarrow \quad U_{R1} + U_{R2} + U_{R3} - U_{ges} = 0$$

3.7.2 Proving the Properties of a Series Circuit of Resistors

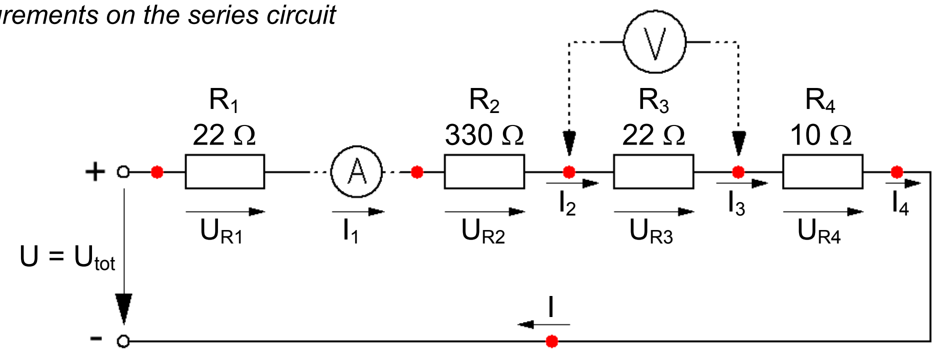
It is to be shown by measurements, that in a series connection of resistors:-

… the current is the same at all points in the circuit
… the sum of all partial voltages is equal to the total voltage
… the sum of individual resistors is equal to the total resistance.

- Assemble the exercise circuit on the Board (Fig. 3.7.2.1).
- Use the fixed voltage source, U = 15 V for $U = U_{tot}$.
- Ensure that for current measurements at the test points between the individual resistors, the circuit can be opened.

Note: In section 3.7.4, details are given on how to modify the circuit with a minimum of re-plugging.

Fig. 3.7.2.1: Measurements on the series circuit



- First, check on the voltmeter that the input voltage is 15 V. Enter the value in table 3.7.2.2.
- Now, measure the currents I and I_1 to I_4 and complete the table.

Current [mA]					Voltage [V]				
I	**I_1**	**I_2**	**I_3**	**I_4**	**U (U_{tot})**	**U_{R1}**	**U_{R2}**	**U_{R3}**	**U_{R4}**

Table 3.7.2.2: Measured values, Series circuit

- Measure the partial voltages across the resistors R_1 to R_4. Enter the values measured in table 3.7.2.2.
- Formulate a statement with regard to the current measured in the series circuit.

- Evaluate the measurements of U_{R1} and U_{R3}. In your answer, use the term 'voltage drop' (where applicable).

- Calculate the total voltage U_{tot} from the partial voltages measured and evaluate your result.

- Verify the nominal values of the individual resistors, by calculation.

- Calculate the total resistance of the series circuit from the values of individual resistors.

- Calculate the total resistance of the series circuit from the input voltage and current.

3.7.3 Tasks / Questions

- Check whether the maximum permissible power dissipation (2 W) has been exceeded at any of the resistors used in the circuit of Fig. 3.7.2.1. Verify this, using only **one** calculation.

Result:

- What is the total power supplied by the voltage source?

- In the circuit in Fig. 3.7.2.1, R_3 is mechanically destroyed. How does this influence the current? What is the resistance value of the damaged resistor?

- In the circuit in Fig. 3.7.3.1, a protection resistor R_S is connected in series with an NTC. At $\vartheta = 25°C$ and $U_{in} = 20$ V, the current flw stabilises at I = 4 mA. Determine by calculation, the values of: R_{NTC}, R_{tot}, U_{NTC}, U_{RS}.

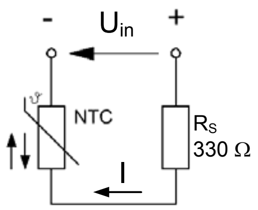


Fig. 3.7.3.1: Series circuit with NTC

- How can the NTC without protection resistor R_S be damaged? Describe the function of the protection resistor R_S.

3.7.4 Exercise Assembly on the Electronic Circuits Board

Fig. 3.7.4.1 shows a space-saving possibility of assembling the voltage divider. By removing the bridges between the resistors, or between R_4 and GND, the ammeter can be inserted in the circuit.

The plus pole of the constant voltage source U = 15 V is connected to the upper row of interconnected sockets. One connection of R_1 is plugged into this row of sockets.

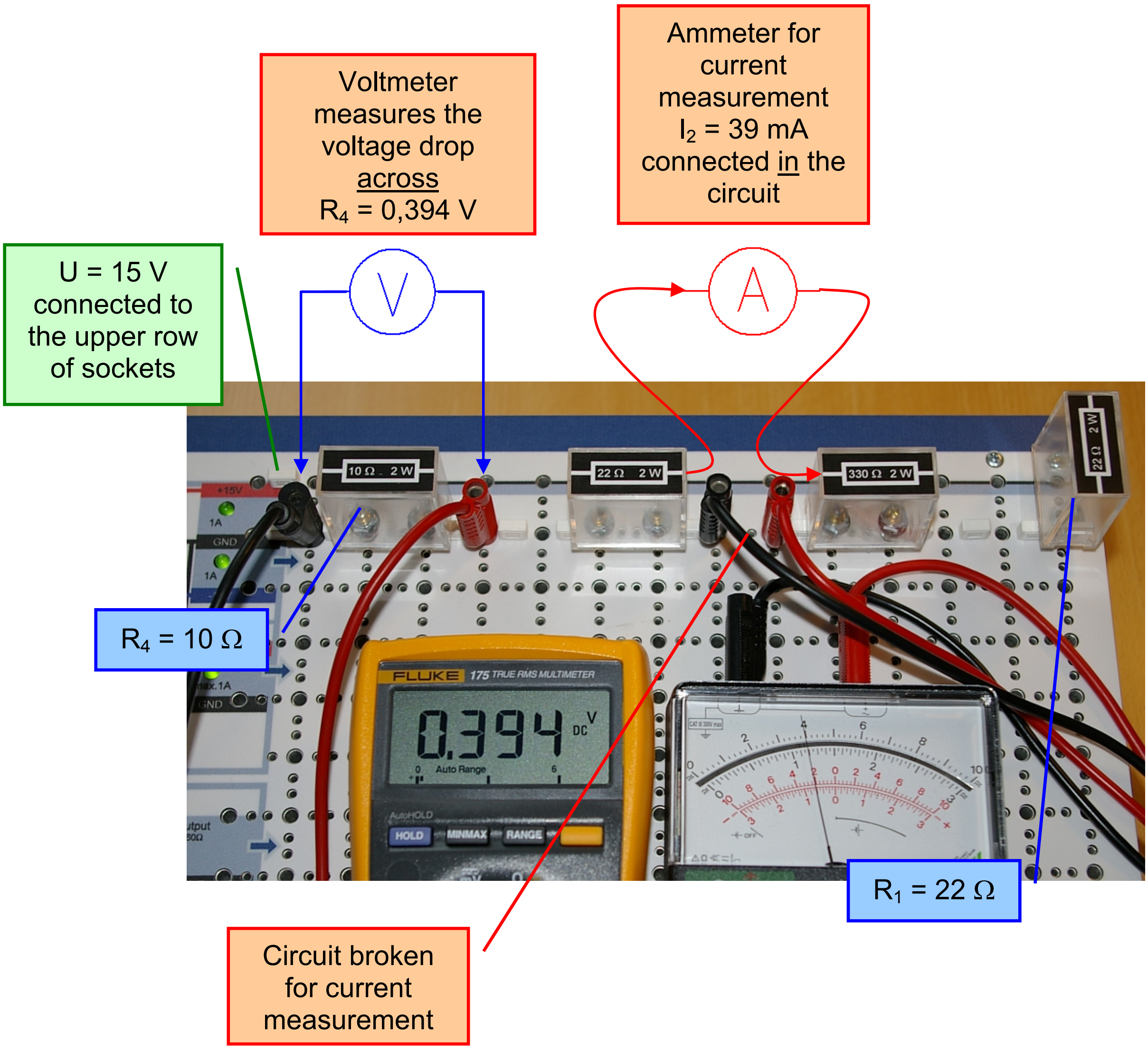


Fig. 3.7.4.1: Exercise layout, 'Series circuit of 4 resistors'

3.8 Parallel Connection of Resistors

3.8.1 Properties of a Parallel Circuit

The same voltage is effective across each individual resistor in a parallel circuit as in Fig. 3.8.1.1. All upper ends of the resistors are connected to plus and all lower ends, to the negative pole of the input voltage. Therefore, it applies:

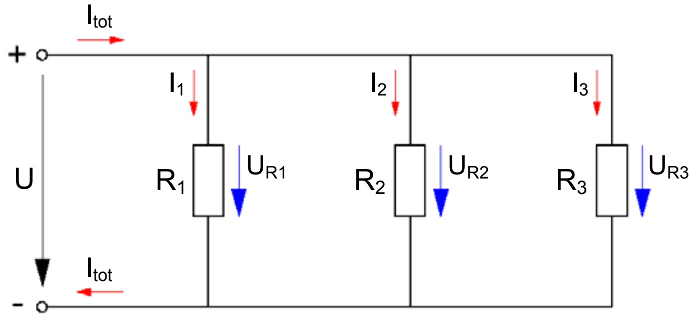


Fig. 3.8.1.1: Parallel circuit of resistors

$$U = U_{R1} = U_{R2} = U_{R3} = U_{Rn}$$

If there is a voltage difference between the ends of a resistor or consumer, a current flows through the component. In a parallel circuit, the current in each branch is given by:

$$I_1 = \frac{U}{R_1} \quad ; \quad I_2 = \frac{U}{R_2} \quad ; \quad I_3 = \frac{U}{R_3} \quad ; \quad I_n = \frac{U}{R_n}$$

The branch currents in a parallel circuit are added to give the total current flow, I_{tot}:

$$I_{tot} = I_1 + I_2 + I_3 + \ldots + I_n$$

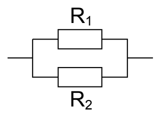
The current, I_{tot} flowing from the plus pole of the input voltage is divided through the individual resistors. Thus the term, **'voltage divider'**. If a resistor is connected in parallel to an existing resistor, the current finds an extra path for a charge carrier balance between the poles of the voltage source.

A total resistance R_{tot}, has an effect on the voltage that is smaller than the smallest individual resistor. This is given by the formula:

$$R_{tot} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{Rn}}$$

The relatively complicated formula for a parallel circuit can be simplified for 2 special cases. With only 2 resistors in parallel, the formula becomes:

$$R_{tot} = \frac{R_1 \cdot R_2}{R_1 + R_2}$$



Easier still, is the calculation of the total resistance if all parallel connected resistors have the same value:

$$R_{tot} = \frac{R}{n}$$

n = Number of equal-value resistors

At any point in a circuit, the sum of the currents flowing to the point, I_{to} is equal to the sum of the currents flowing away from the point, I_{from}. This statement is known as **'Kirchhoff's first law'**:

Fig. 3.8.1.2 should clarify this statement and Fig. 3.8.1.1 from the current arrows at the side of the resistors.

$$\sum I_{to} = \sum I_{from}$$

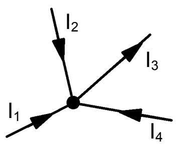


Fig. 3.8.1.2: Kirchhoff's first law

3.8.2. Proving the Properties of a Parallel Circuit of Resistors

It is to be shown by measurements, that in a Parallel connection of resistors:-

… the voltage across all resistors is the same
… the total current equals the sum of all branch currents
… the total resistance is always smaller than the smallest individual resistor.

- Assemble the exercise circuit on the Board (Fig. 3.8.2.1).
- Use the fixed voltage source (+15 V) as input voltage U for the parallel circuit.
- Ensure that for current measurements at the test points between the individual resistors, the circuit can be opened. (A possibility of the layout of the plug-in components will be found in section 3.8.4.)

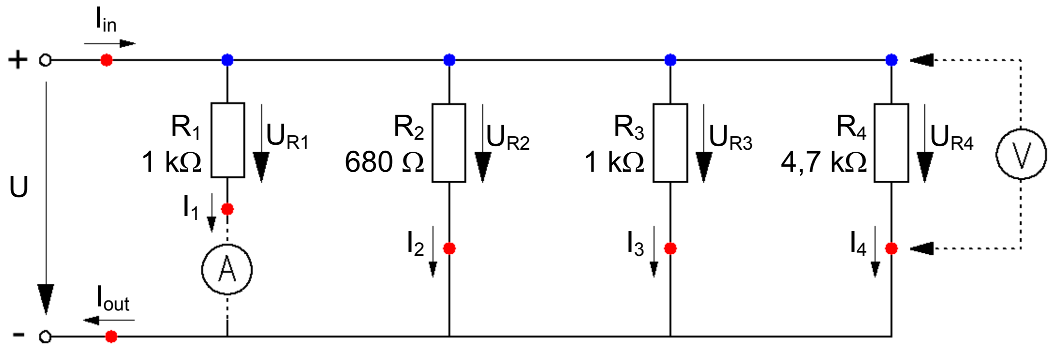


Fig. 3.8.2.1: Measurements on the parallel circuit

- First, check on the voltmeter that the input voltage is 15 V. Enter the value in table 3.8.2.2.
- Now, measure the voltage drop across the resistors (U_{R1} to U_{R4}) and complete the table.

Current [mA]						Voltage [V]				
I_{in} (I_{tot})	I_{out} (I_{tot})	I_1	I_2	I_3	I_4	U	U_{R1}	U_{R2}	U_{R3}	U_{R4}

Table 3.8.2.2: Measured values, Parallel circuit

- Measure the branch currents in the resistor branches R_1 to R_4. Enter the values measured in table 3.8.2.2.
- Measure the total current, I_{tot} before the resistors (I_{in}) and after (I_{out}). Complete table 3.8.2.2.

3.8.3 Tasks / Questions

- Explain the results of your voltage measurements U and U_{R1} to U_{R4} with a summarising statement.

- What can be said of the values measured for I_1 and I_3? Your explanation should based on Ohm's law.

- Calculate the total current I_{tot} (= I_{in} = I_{from}) from the branch currents and evaluate the result.

- Verify the nominal value of he individual resistors by calculation.

- Without calculation, what estimate can be made for the value of the total resistance in the circuit, R_{tot}?

- Confirm your estimation of R_{tot} in the parallel circuit, by calculation.

- Calculate the total resistance of the parallel circuit from the input voltage and the total current measured, I_{tot}. Compare the result with that from the calculation using nominal values.

- Check whether the maximum permissible power dissipation (2 W) has been exceeded at any of the resistors used in the circuit. Verify this, using only **one** calculation.

  Result:

- What is the total power supplied by the voltage source?

- Remove resistors R_1 = 1 kΩ and R_2 = 680 Ω from the circuit (or a bridge, as in Fig. 3.8.3.1).

- Calculate the total resistance for the remaining parallel circuit of R_3 = 1 kΩ and R_4 = 4,7 kΩ, using their nominal values.

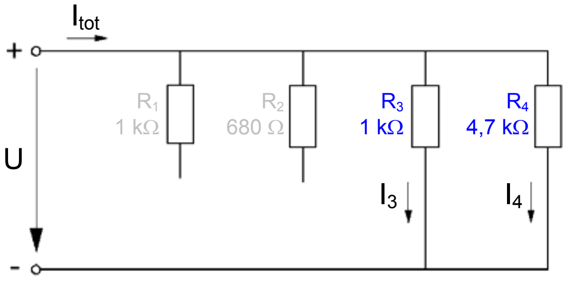


Fig. 3.8.3.1: Two resistors in parallel

- Calculate the total resistance by Ohm's law from U and the branch currents I_3, I_4. Are new measurements for I_3, I_4 necessary? Give reasons for your answer.

- How does the total resistance of the circuit change when the bridge for R_2 is inserted again and at the same time, the branch with R_3 opened?

- What value of resistor must be used to replace the three 1 kΩ resistors in the parallel circuit of Fig. 3.8.3.2 with a single resistor?

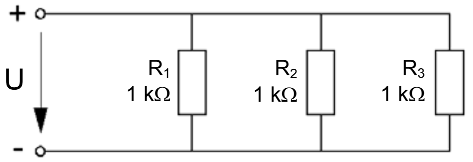


Fig. 3.8.3.2: Parallel circuit of three 1 kΩ resistors

- What is the power dissipation of the circuit in Fig. 3.8.3.2, when the input voltage applied is 15 V? For the calculation, use only voltage and resistance.

- Assemble the circuit of Fig. 3.8.3.2 on the Board. Use the fixed voltage source of U = 15 V. Measure the currents in the resistor branches R_1 to R_3. Calculate the total current.

I_1	I_2	I_3

- Confirm your previous calculation of dissipated power (from voltage and resistance values), with a check calculation using the value of current measured.

- At an ambient temperature of ϑ = 18°C, the parallel circuit of PTC and R_1 loads the voltage source with a total resistance of 5 kΩ. What resistance value has the PTC?

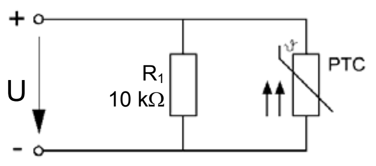


Fig.: 3.8.3.3: Parallel circuit of PTC and 10 kΩ resistor

3.8.4 Exercise Assembly on the Electronic Circuits Board

Fig. 3.8.4.1 shows a space-saving possibility of assembling the voltage divider. By removing the bridges below the resistors, the ammeter can be inserted in the circuit.

The plus pole of the constant voltage source U = 15 V is connected to the upper row of interconnected sockets, that supplies voltage to the upper contact of the resistors.

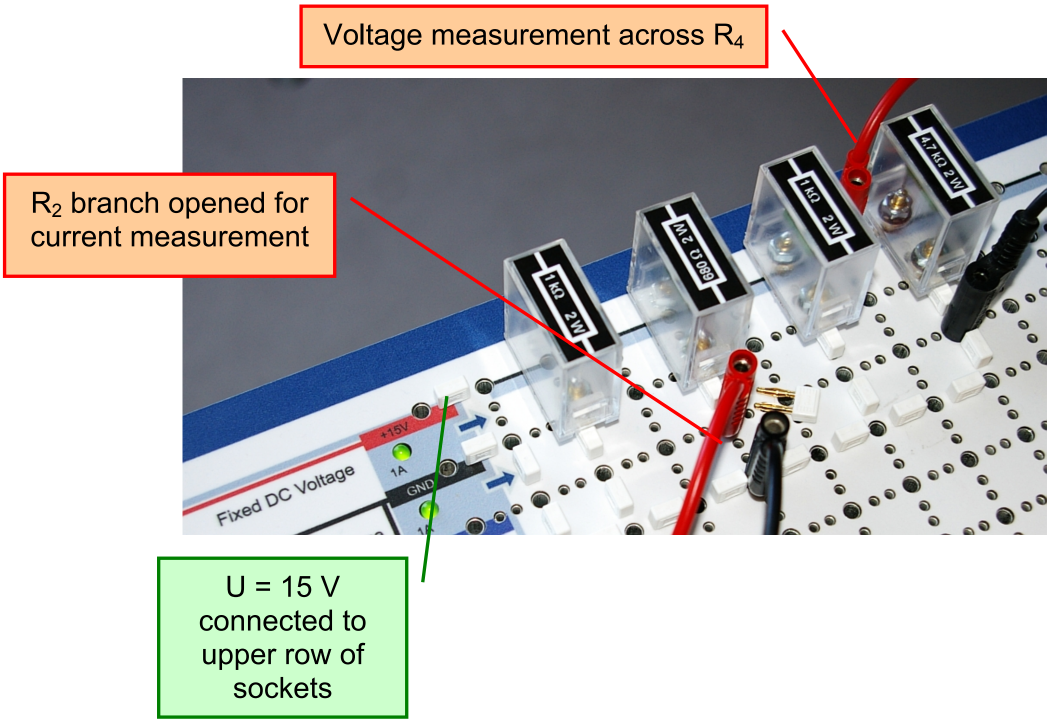


Fig. 3.8.4.1: Exercise assembly, Parallel circuit of 4 resistors

3.9 Combinations of Series and Parallel Circuits

Electronic circuits often incorporate a mixture of voltage and current dividing circuits. A simple example is shown in Fig. 3.9.1.1.

3.9.1 Analysis

To simplify the analysis of resistor combinations, it is usual to split the circuit into sections, where each section corresponds to a pure series or parallel connection.

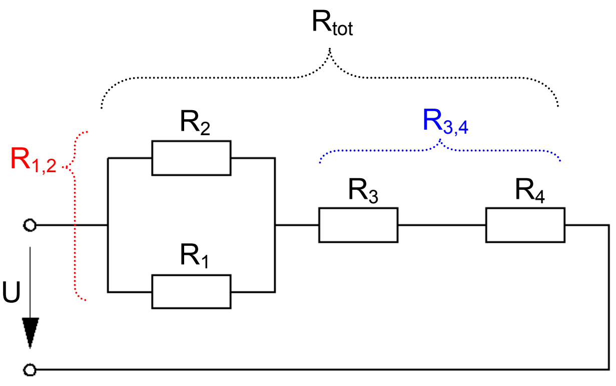


Fig. 3.9.1.1: Combination of series and parallel circuits

For example, if the total resistance of the circuit in Fig. 3.9.1.1 is required first, a so-called equivalent resistance must be formed for R_1 and R_2 ($R_{1,2}$).

$$R_{1,2} = \frac{R_1 \cdot R_2}{R_1 + R_2}$$

The next step is to calculate the resultant value of $R_{3,4}$:

$$R_{3,4} = R_3 + R_4$$

Finally, the total resistance R_{tot} is then given by:

$$R_{ges} = R_{1,2} + R_{3,4}$$

A similar method is also used for voltages and currents

3.9.2 Practical Exercises with Mixed Resistor Circuits

A circuit analysis will be practiced on the example circuit of a combination of series and parallel connections.

<u>Resistor network 1</u>

- Assemble the circuit of Fig. 3.9.2.1 on the Electronic Circuits Board. Ensure that it will be possible to open the circuit at the locations required for current measurements (assembly notes will be found in section 3.9.4).

- Set the voltage at the input of the circuit, to U = 28 V. (Check the value on the multimeter and enter the value in table 3.9.2.2.

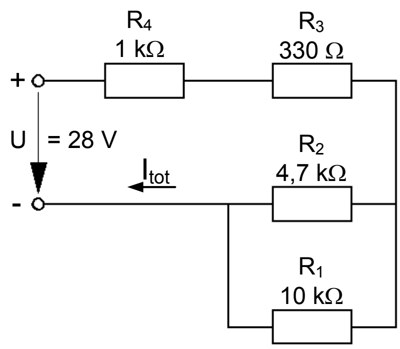


Fig. 3.9.2.1: Resistor network 1

- Measure the voltages and currents and enter the values in table 3.9.2.2.

Current [mA]			Voltage [V]				
I_{tot}	I_{R1}	I_{R2}	U	U_{R1}	U_{R2}	U_{R3}	U_{R4}

Table 3.9.2.2: Values measured in resistor network 1

- Using the rules for series and parallel circuits, calculate the total resistance R_{tot} of the circuit from the nominal values of the individual resistors.

- Check the nominal values and calculated resistor values (R_{tot}, $R_{1,2}$, $R_{3,4}$) using the measured values from table 3.9.2.2. Explain any deviations.

Resistor network 2

- Assemble the circuit of Fig. 3.9.2.3 on the Electronic Circuits Board. Ensure that all measurement points for voltage and current, are easily accessible (assembly notes will be found in section 3.9.4).

- Set the voltage at the input of the circuit, to U = 18 V. (Check the value on the multimeter and enter the value in table 3.9.2.4).

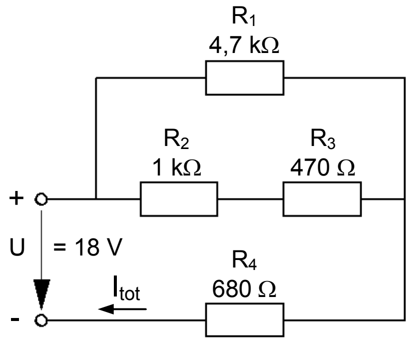


Fig. 3.9.2.3: Resistor network 2

- Measure the voltages and currents and enter the values in table 3.9.2.4.

Current [mA]			Voltage [V]				
I_{tot}	I_{R1}	$I_{R2,3}$	U	U_{R1}	U_{R2}	U_{R3}	U_{R4}

Table 3.9.2.4: Values measured in resistor network 2

- Calculate the total resistance R_{tot} of the circuit from the nominal values of the individual resistors.

- Check the nominal values and calculated resistor values (R_{tot}, $R_{2,3}$, $R_{1,2,3}$) using the measured values from table 3.9.2.4.

3.9.3 Tasks / Questions

Use the nominal values of resistance for all questions.

- What are the values of total current I_{tot} and I_{R1}, when resistor R_3 in the resistor network of Fig. 3.9.2.1 is damaged (high resistance)

- How large does R_{tot} become (Fig. 3.9.2.1), when R_2 is bridged with a piece of wire?

- In which direction does the total current I_{tot} in the circuit of Fig. 3.9.2.3 change, when R_2 becomes high-resistive?

- How large is the total resistance R_{tot}, when the individual resistor R_1 becomes high-resistive in the circuit of Fig. 3.9.2.3?

Fig. 3.9.3.1 shows the circuit of a light barrier. When the focussed beam of light strikes the LDR, a maximum current flows in the circuit of I_{tot} = 37 mA. If the light beam is interrupted, the resistance of the LDR increases up to the MΩ range. The voltage across R_{LDR} produced by the change in the light intensity, is processed by an evaluation unit that has an input resistance of R_e = 1 kΩ.

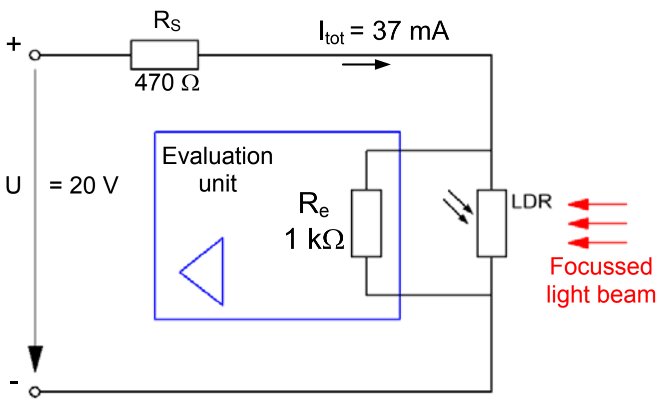


Fig. 3.9.3.1: Light barrier

- For further processing, the evaluation unit requires an explicit voltage change: U_{light} < 5 V ; U_{dark} > 10 V. Are these conditions satisfied for evaluating the information from the light barrier?

- To what value does $R_{LDR,Re}$ fall, when the LDR is illuminated?

3.9.4 Exercise Assembly on the Electronic Circuits Board

Figs. 3.9.4.1 and 3.9.4.2 show a practical assembly layout for the circuits of mixed resistor connections. Particular attention has been paid to the accessibility of the test points required for current and voltage measurements.

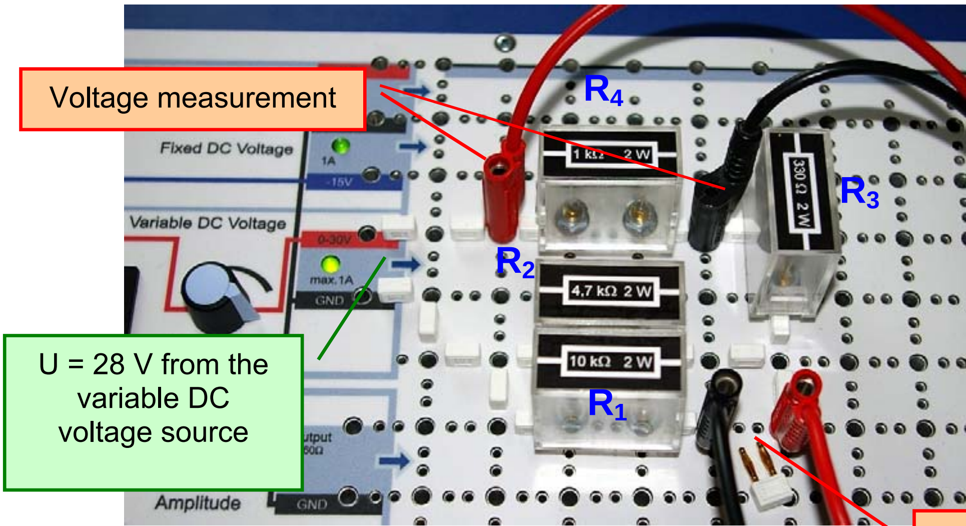


Fig. 3.9.4.1: Measurements on resistor network 1

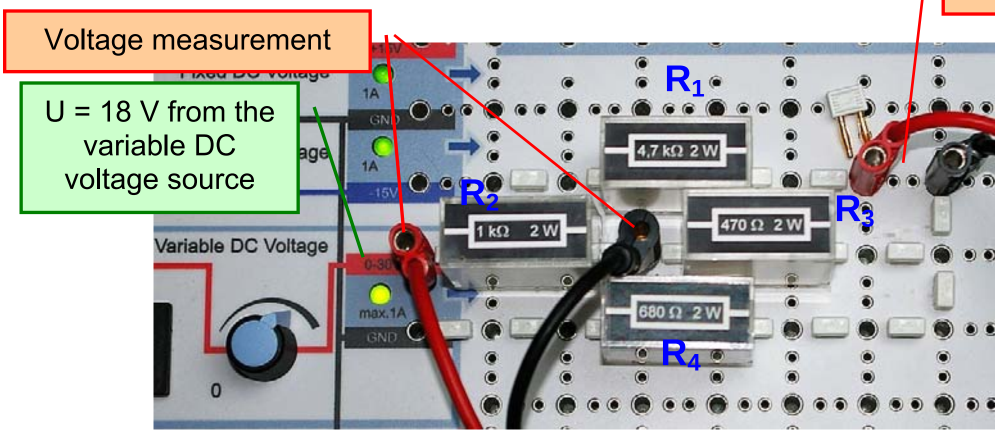


Fig. 3.9.4.2: Measurements on resistor network 2

3.10 The Off-load Voltage Divider

3.10.1 Properties of an Off-load Voltage Divider

In electrical engineering and electronics, it is often necessary to split a specific voltage into smaller partial voltages. A voltage divider solves this problem very easily. In its simplest form, it consists of two resistors connected in series (Fig. 3.10.1.1). Two connections form the input for the input voltage (U). At the output side, a partial voltage (U_2) is available across the resistor.

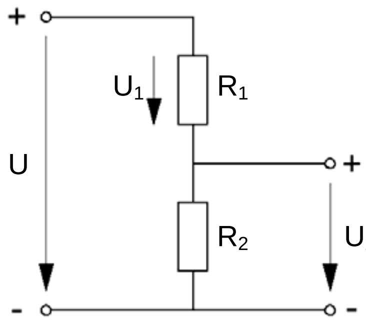


Fig. 3.10.1.1: Off-load voltage divider

Since the same current flows through both resistors, the voltage U, is divided according to their resistance values:

$$\frac{U_1}{U_2} = \frac{R_1}{R_2}$$

The relationship between the input and output voltages of the circuit can also be expressed by a proportional equation: The voltage U_2, is proportional to the total voltage U, as R_2 is proportional to the sum of the resistances.

$$\frac{U_2}{U} = \frac{R_2}{R_1 + R_2} \quad \rightarrow \quad U_2 = U \cdot \frac{R_2}{R_1 + R_2}$$

In practice, a voltage divider is often required that has a variable output voltage. In his case, a potentiometer is used as the output resistor (Fig. 3.10.1.2). A slider in the potentiometer effectively splits the resistance material in two sections, i.e. R_1 and R_2. By moving the slider, the ratio R_1/R_2 can be varied and thus, the partial voltage available at the output can be adjusted.

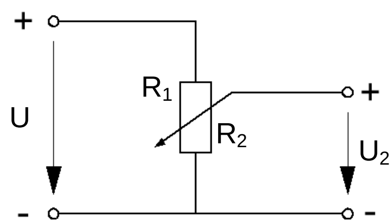


Fig. 3.10.1.2: Potentiometer

3.10.2 Practical Exercises with Off-load Voltage Dividers

<u>Voltage divider with fixed resistance ratio</u>

- For the circuit in Fig. 3.10.2.1, calculate the output voltage U_2 and the voltage U_1.

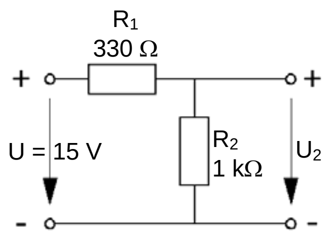


Fig. 3.10.2.1: Voltage divider

Assemble the circuit in Fig. 3.10.2.1 on the Electronic Circuits Board. Apply a voltage of U = 15 V to the input of the voltage divider (check the input voltage on a multimeter).

- Check the calculated voltage values for U_1 and U_2 by measurement.

- How do you explain the small deviations between measured values and calculated values?

<u>Voltage divider with variable resistance ratio (potentiometer)</u>

- Insert the potentiometer P = 1 kΩ, into the circuit of Fig. 3.10.2.2 on the Electronic Circuits Board. Use an input voltage of U = 12 V (check the set value, on a multimeter).

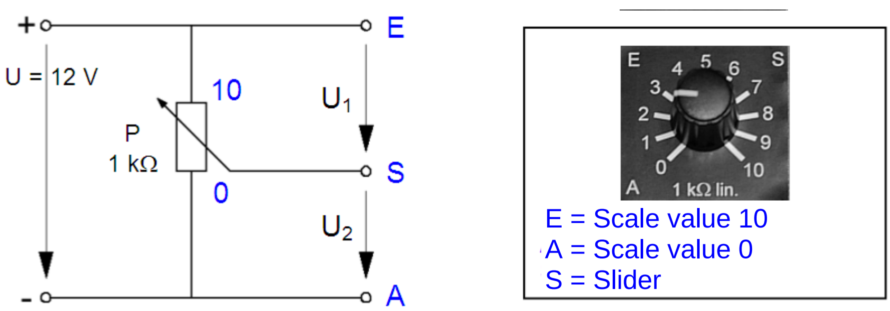


Fig. 3.10.2.2: Potentiometer

- Measure the output voltages U_1 and U_2 in relation to the slider setting (scale values). Enter the values measured in table 3.10.2.3.

Scale	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
U_1 [V]											
U_2 [V]											

Table 3.10.2.3: Voltage measurements at the potentiometer

From the values measured, the characteristics U_1 = f(scale value) and U_2 = f(scale value) will now be drawn.

- What form of curve for the characteristics is expected and why?

- Plot the values from the table in the chart (Fig. 3.10.2.4) and draw the characteristics U_1 = f(scale value) and U_2 = f(scale value).

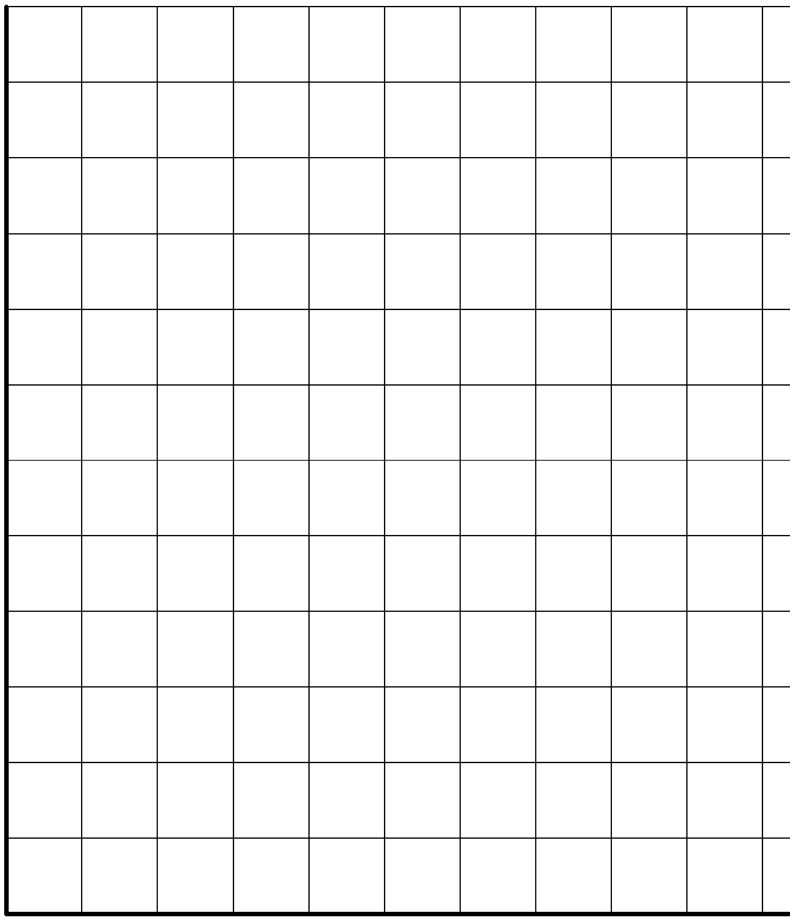


Fig. 3.10.2.4 Potentiometer characteristic

- How do you explain the slight non-linearity of the characteristics?

- What is the result of adding the voltage values of both characteristics at any optional setting of the slider? Explain your answer with an example for the '5' setting.

- Calculate the resistance of R_2 at a slider setting (scale value) of '2'.

3.11 The Loaded Voltage Divider

The partial voltage, output from a voltage divider, is seldom without a load. For a divider to fulfil its purpose, the output voltage U_A supplies the next circuit where the load current I_L flows (Fig. 3.11.1). The circuit here, has a load resistor R_L, that is in parallel to R_2 of the voltage divider (Fig. 3.11.1).

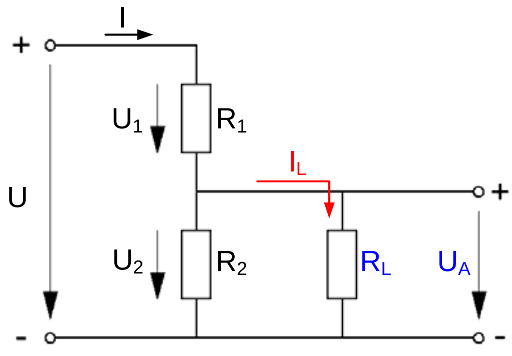


Fig. 3.11.1: Loaded voltage divider

3.11.1 Properties of a Loaded Voltage Divider

A loaded voltage divider represents a combination of a series and a parallel circuit. The equivalent resistance $R_{2,L}$ of the parallel circuit of R_2 and R_L can be calculated as shown here:

$$R_{2,L} = \frac{R_2 \cdot R_L}{R_2 + R_L}$$

The output voltage U_A of a loaded voltage divider can be calculated by using the equivalent resistance $R_{2,L}$:

$$\frac{U_A}{U} = \frac{R_{2,L}}{R_1 + R_{2,L}} \quad \Leftrightarrow \quad U_A = U \cdot \frac{R_{2,L}}{R_1 + R_{2,L}}$$

Providing that the load current I_L is small compared to the current flow through R_2, the loading causes only a small reduction in the output voltage. To achieve this, R_2 must be much smaller than R_L ($R_2 << R_L$). However, an output resistor R_2 with a very small resistance value causes a very high total current I, which increase the heat loss in the voltage divider. In practice, the resistors in the voltage divider are selected so that the current flow through R_2 is double the value of I_L.

3.11.2 Practical Exercises with Loaded Voltage Dividers

<u>**Loaded** voltage divider with fixed resistance ratio</u>

The voltage divider shown in Fig. 3.11.2.1 is to provide half of the input voltage U = 12 V as an output voltage U_A = 6 V (therefore, $R_1 = R_2$). Irrespective of the loading variations due to different consumers (R_L), the following conditions should be observed:

1. The output voltage U_A must not fall below 5,5 V with a minimum load resistor of $R_{L\,min}$ = 10 kΩ.
2. The maximum load current I_L, must not exceed one-fifth of the current flow through R_2 even at the maximum load (= $R_{L\,min}$).
3. The power dissipated at the voltage divider should exceed 100 mW.

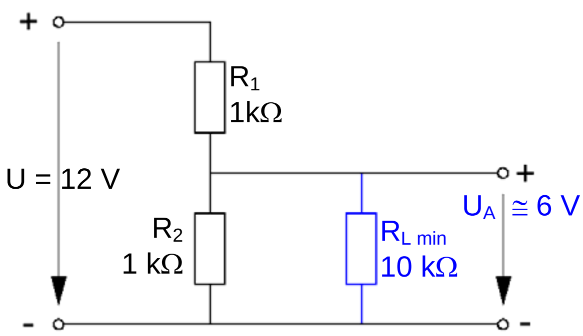


Fig. 3.11.2.1: Exercise with a loaded voltage divider

- Assemble the circuit in Fig. 3.11.2.1 on the Electronic Circuits Board (Notes on assembly will be found in section 3.11.3). Apply a voltage of U = 12 V to the input of the voltage divider (check the input voltage on a multimeter).

- Check by measurement, the actual values of current and voltage to ensure that the circuit adheres to conditions 1 and 2 (calculate condition 3 on the basis of the values measured).

Table 3.11.2.2: Measurements on a loaded voltage divider

U	**$U_{A\ off\text{-}load}$**	**$U_{A\ loaded\ (10\ K\Omega)}$**	**I_L**	**I_{R2}**

- Calculate the output voltage U_A when the voltage divider is loaded with a resistor of R_L = 680 Ω.

- Replace R_L = 10 kΩ in Fig. 3.11.2.1 with R_L = 680 Ω and check the above calculation by measurement.

U_A =

<u>**Loaded** voltage divider with variable resistance ratio (potentiometer)</u>

- Apply a voltage of U = 12 V to the input of the potentiometers P = 1 kΩ, as shown in Fig. 3.11.2.3 (check the set value, on a multimeter).

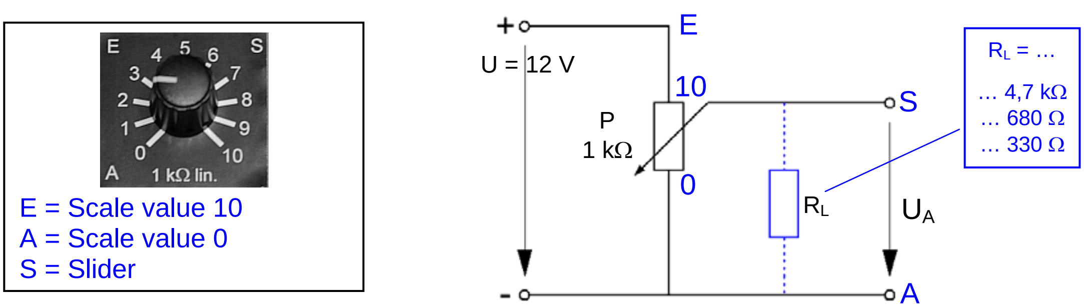


Fig. 3.11.2.3: Potentiometer with loaded output

- The output of the potentiometer will now be loaded with 3 different values of resistance, in sequence (330 Ω, 680 Ω, 4,7 kΩ). For each resistor, measure the output voltage U_A as a function of the slider setting (scale value). Enter the values measured into table 3.11.2.4.

Scale	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
U_A [V] (330 Ω)											
U_A [V] (680 Ω)											
U_A [V] (4,7 kΩ)											

Table 3.11.2.4: Voltage measurements on a loaded potentiometer

- Plot the values from the table in the chart (Fig. 3.11.2.5) and draw the characteristics U_A = f(scale value).

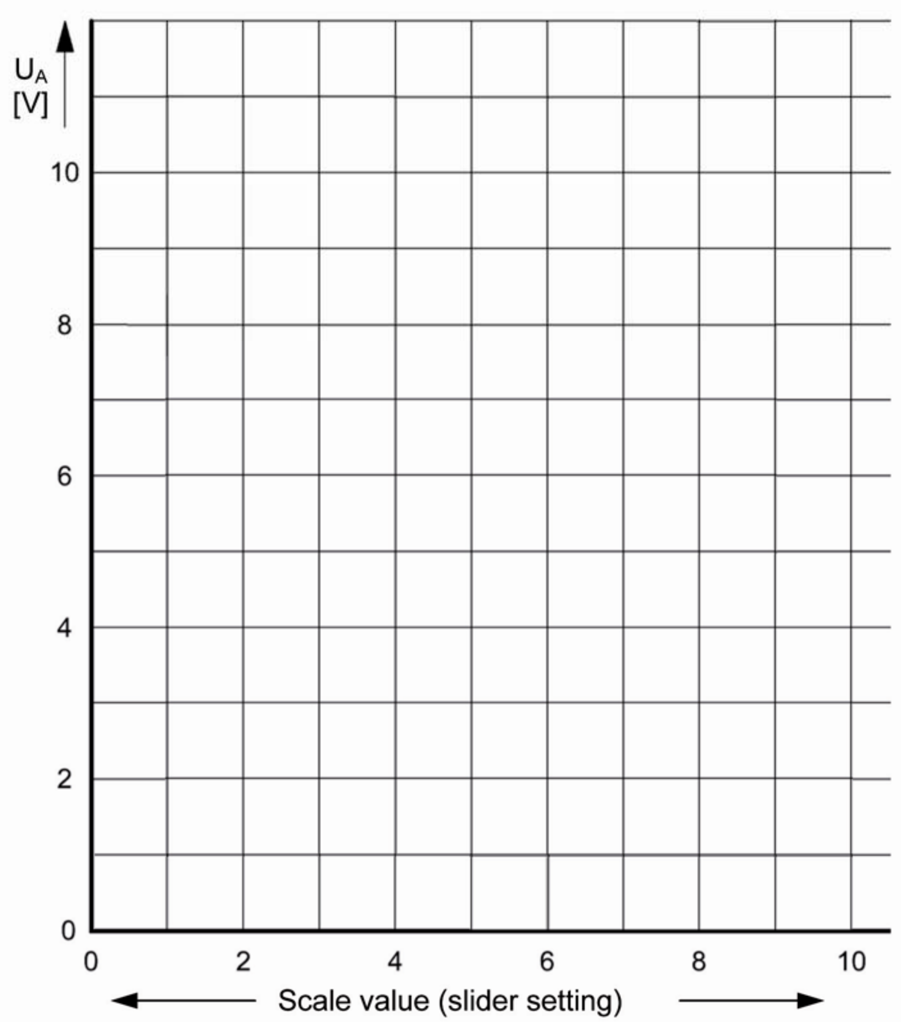


Fig. 3.11.2.5: Characteristics of the potentiometer with different loads

- Explain why the characteristic curves are not congruent.

- Calculate the output voltage U_A at the mid-position of the slider and a load resistor of R_L = 680 Ω.

- Compare the calculated values with the corresponding measured values in table 3.11.2.4. If the values differ, how do you explain the deviations?

3.11.3 Exercise Assembly on the Electronic Circuits Board

Loaded voltage divider with fixed resistance ratio

The layout shown in Fig. 3.11.3.1 ensures that all test points are easily accessible. All 'GND' (= earth) connections on the voltage source, should be connected together. Thus, it is possible with this layout, to connect the lower end of the voltage divider to the 'GND' connection of an external voltage source.

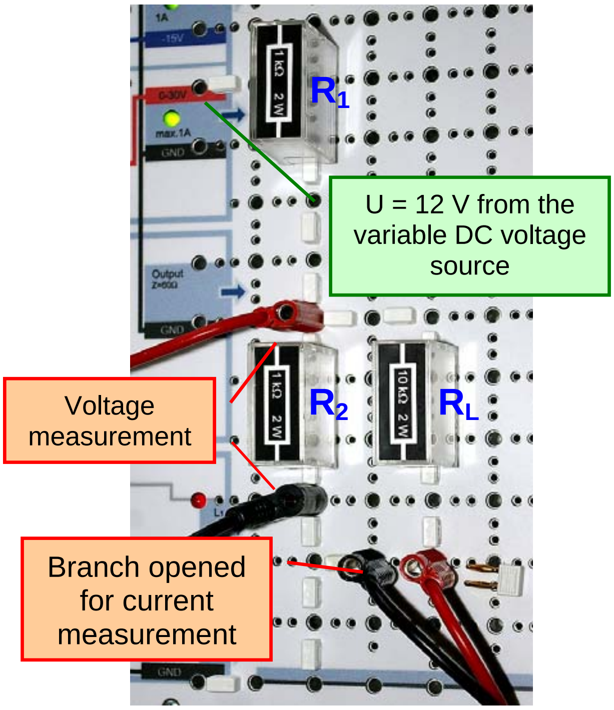


Fig. 3.11.3.1: Measurements on a loaded voltage divider with fixed resistance ratio

<u>**Loaded** voltage divider with variable resistance ratio (potentiometer)</u>

Fig. 3.11.3.2 shows a layout of the plug-in components for recording the characteristics of a loaded potentiometer (R_L = 330 Ω). The fourth, unmarked connection or pin, on the potentiometer is insulated from the housing. Thus, if required, the connections (pins) 'A' or 'S' can be connected to other components, by using this pin. In Fig. 3.11.3.2, the negative pole of the voltage source is connected via 'A' and the insulated pin 4, to the lower end of the load resistor R_L.

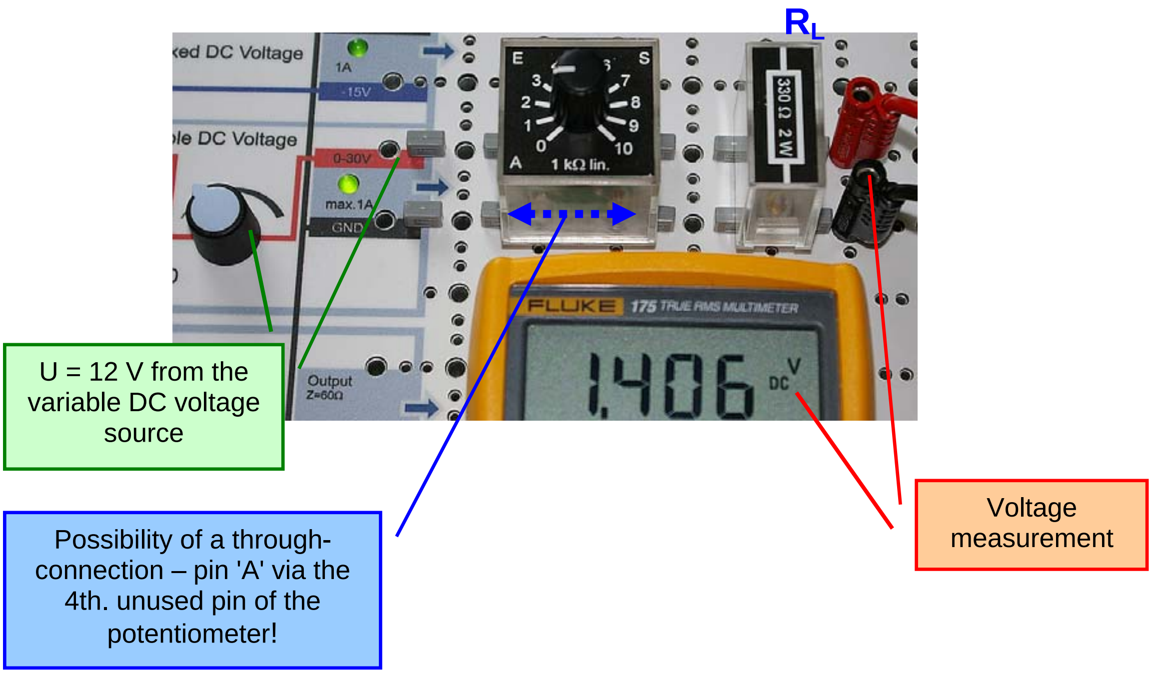
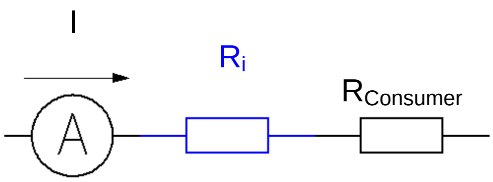


Fig. 3.11.3.2: Measurements on a loaded voltage divider with a potentiometer

4. Voltage and Current Error Circuits

4.1 Principles of Voltage and Current Measurement

For measuring the basic variables of electric voltage U (or V) and current I, test meters must be inserted in the circuit. For measuring voltage, a voltmeter is connected in parallel to the consumer (Fig. 4.1.1, right hand side). For measuring the current, the circuit must be broken and an ammeter inserted at the break, i.e. connected in series with the consumer. This ensures that the same current flows through the meter and consumer (Fig. 4.1.1, left hand side). In practice, current measurements are avoided where possible due to the problems associated with inserting an ammeter into the circuit; sometimes, it is not even possible (for example, printed tracks on a PCB).



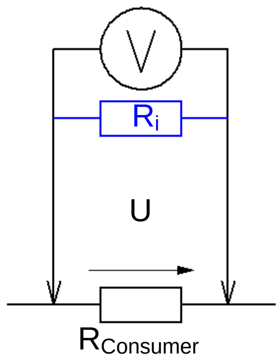


Fig. 4.1.1: Principles of current and voltage measurement

Considering only the physical relationships, both types of measurement will falsify the variables measured. Test meters have an internal resistance R_i, that influences the resistance ratio's in the circuit (Fig. 4.1.1). Since a voltmeter is connected in parallel to the consumer, its internal resistance must be as large as possible (in the order of MΩ, depending on the measurement range selected).

The internal resistance of an ammeter on the other hand, connected in series with a consumer, must be as small as possible (a few Ω, depending on the measurement range).

Since the ideal conditions for current ($R_i = 0$) and voltage measurements ($R_i = \infty$) cannot be satisfied in practice, actual values measured are always slightly wrong and usually, the measurement error introduced is small enough to be ignored. Occasionally though, an incorrect measurement can upset logic thinking in the case of fault-finding. It is also possible in isolated cases, that the introduction of a voltmeter in sensitive electronic circuits upsets their function.

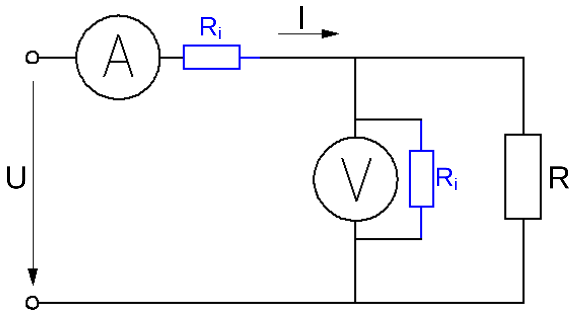
Therefore, careful considerations are essential **before** making any measurements, of the effect of test meters on the test object and the expected results of measurements.

This applies in particular when voltage and current at a consumer, are to be measured at the same time. The method of connecting both test meters depends on the resistance value of the consumer. For low-resistive consumers (Ω), the voltmeter and ammeter are connected as shown in Fig. 4.1.2 (current error circuit). At high-resistive consumers (kΩ and more), the connections shown in Fig. 4.1.3 are used (voltage error circuit).

Both variations result in a very small unavoidable measurement error.

In the **current error circuit** the ammeter also indicates the error current flowing through the internal resistance of the voltmeter. Since the resistance of the consumer is very small compared to R_i ($R << R_i$), the current error acceptable.

Fig. 4.1.2: Current error circuit



When the **voltage error circuit** is used, the voltmeter measures the voltage drop across the voltage divider made up of consumer and R_i of the ammeter. Since R_i of the ammeter is only a few ohms (or less), and R is at least a few kΩ ($R >> R_i$), the voltage error can be ignored.

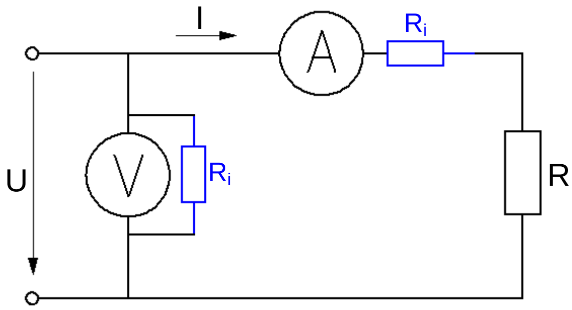


Fig. 4.1.3: Voltage error circuit

4.2 Use of Voltage and Current Error Circuits

The improved measurement accuracy of a current error circuit with low-resistive consumers (here, R = 33 Ω), will be proved by measurements. This will be followed by the proof for a combination of a high-resistive consumer (here, R = 10 kΩ) using a voltage error circuit.

- First, with a digital multimeter, measure the exact value of resistance of the two resistors and enter the values in tables 4.2.1 and 4.2.2. Note: If an accurate test meter is not available, enter the nominal values in the tables.
- Assemble the **current** error circuit in Fig. 4.1.2 on the Board. Set the output of the voltage source to U = 5 V.
- Measure current and voltage for both consumers (resistors) and enter the values measured in table 4.2.1.

R measured	**I [mA]**	**U [V]**	**R calculated**	**ΔR**

Table 4.2.1: Values measured with a current error circuit

- Assemble the **voltage** error circuit in Fig. 4.1.3 on the Board. Set the output of the voltage source to U = 5 V.
- Measure current and voltage for both consumers (resistors) and enter the values measured in table 4.2.2.

R measured	I [mA]	U [V]	R calculated	ΔR

Table 4.2.2: Values measured with a voltage error circuit

- Determine the difference ΔR between measured and calculated values of resistance. Enter the results in tables 4.2.1 and 4.2.2.
- With which error circuit can the value of the low-resistive consumer / resistance be precisely calculated because the measured values are more accurate?
- Which error circuit produces smaller measurement errors for the high-resistive consumer / resistance?

5. Equivalent Voltage Sources

Up to now, voltage sources have only been considered as an ideal case. This means that the set voltage or fixed nominal voltage remains the same, irrespective of the operating conditions. To achieve such constant voltage, some form of electronic stabilising circuit is necessary. Voltage sources without or with only slight stabilising, cannot maintain a constant voltage when a load is applied.

To avoid the necessity of examining the sometimes complex internal circuits of a voltage source and the circuit supplied by the voltage, use is often made of the so-called **equivalent voltage source** and apply the decisive properties.

5.1 Properties of an Equivalent Voltage Source

All voltage sources can be considered as consisting of a combination of two sections: The actual voltage generator that provides the **source voltage U_0**, and an **internal resistance R_i** (Fig. 5.1.1). Thus, the actual voltage available at the output – known as the '**terminal voltage**' **U_K** – is reduced by the voltage drop U_{Ri} across the internal resistance:

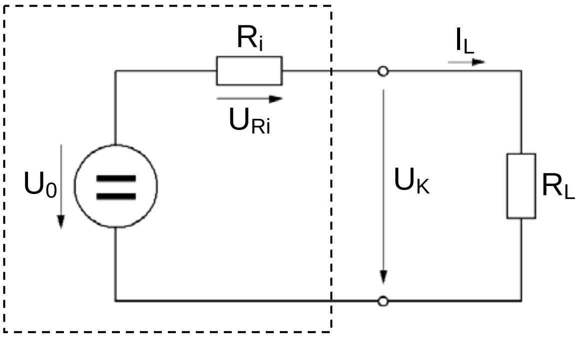


Fig. 5.1.1: Equivalent voltage source

$$U_K = U_0 - U_{Ri} \quad \text{and} \quad U_{Ri} = R_i \cdot I_L$$

$$\Rightarrow \quad U_K = U_0 - R_i \cdot I_L$$

The voltage drop U_{Ri} across the internal resistance increases according to Ohm's law, when more current is drawn from the voltage source. This is the case when the source is loaded with a small load resistance, R_L.

The load current I_L is given by :

$$I_L = \frac{U_0}{R_i + R_L}$$

After substituting the load current equation and transformation, the terminal voltage U_K can be calculated from:

$$U_K = U_0 \cdot \frac{R_L}{R_i + R_L}$$

A differentiation is made between two limiting conditions; i.e. **off-load** ($R_L = \infty$) and **short circuit** ($R_L = 0$).

When **off-load** (output terminals, open-circuit), there is no flow of load current, thus there is no voltage drop across the internal resistance of the voltage source. In this case, the terminal voltage U_K corresponds to the source voltage, U_0.

$$U_K = U_0 \quad | \quad R_L = \infty$$

With a **short circuit** at the output (R_L = 0) the internal resistance limits the flow of current. The short circuit current I_K, is given by:

$$I_K = \frac{U_0}{R_i} \quad \Big| \quad R_L = 0$$

In practice, short circuit (U_K = 0) and **off-load** (I_L = 0) operation have no significance. The two limiting conditions are used merely to define the end points of a characteristic for the voltage source (Fig. 5.1.2). All real applications with a loading resistance R_L, between '0' and 'infinity' also lie on the characteristic.

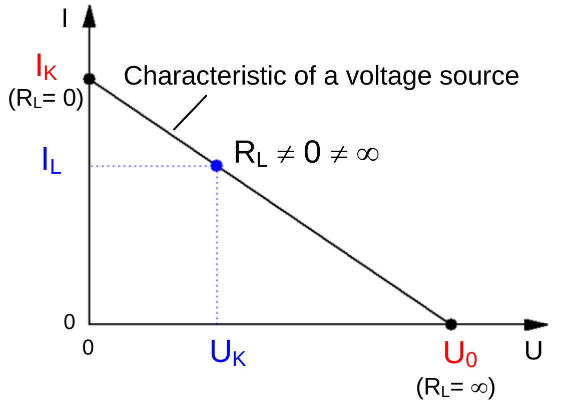


Fig. 5.1.2: Characteristic of a voltage source

5.2 Practical Exercises with an Equivalent Voltage Source

First, the characteristic of an equivalent voltage source will be recorded. Since the Board incorporates only stabilised voltages, an equivalent voltage source will be simulated by an external R_i = 33 Ω (Fig. 5.2.1). The output of the variable voltage supply is set to 3 V and used as the source voltage U_0.

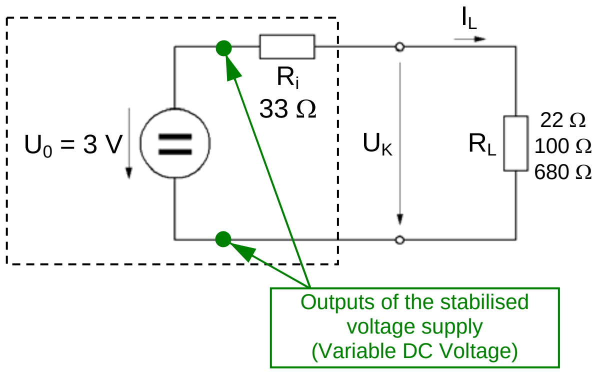


Fig. 5.2.1: Simulation of an equivalent voltage source

- Simulate the equivalent voltage source on the Board, as shown in Fig. 5.2.1.
- In off-load operation, measure the source voltage U_0 and the terminal voltage U_K. Enter the values in table 5.2.2.
- For short circuit operation, measure the short-circuit current, I_K and the source voltage U_0. Consider how short circuit and current measurements can be completed with the same circuit layout. Enter the measured values in table 5.2.2.

Off-load		**Short circuit**		**R_L = 22 Ω**		**R_L = 100 Ω**		**R_L = 680 Ω**	
U_0 [V]	**U_K** [V]	**U_0** [V]	**I_K** [mA]	**U_K** [V]	**I_L** [mA]	**U_K** [V]	**I_L** [mA]	**U_K** [V]	**I_L** [mA]

Table 5.2.2: Values measured on the equivalent voltage source

- Explain the values measured for the source voltage U_0 and the terminal voltage U_K in off-load operation.

- From the measured values, draw the characteristics for off-load and short circuit conditions at the equivalent voltage source, in Fig. 5.2.3.

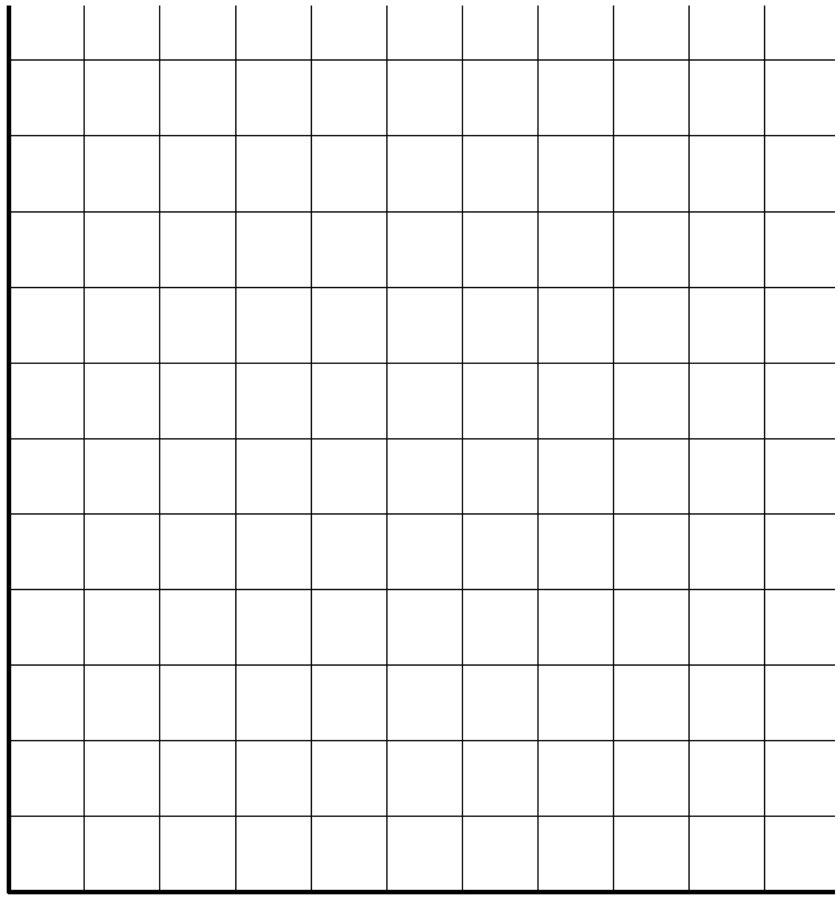


Fig. 5.2.3: Characteristic of the equivalent voltage source

- Now, measure the terminal voltage U_K and load current I_L for the 3 consumers, R_L = 22 / 100 / 680 Ω. Enter the values measured in table 5.2.2.
- Mark the points for the 3 loading conditions on the characteristic in Fig. 5.2.3.
- Calculate the voltage drop across the internal resistance (U_{Ri}) for a consumer of R_L = 22 Ω.

- The voltage source under examination, has an internal resistance R_i of 33 Ω. What changes are occur in the characteristic when an equivalent voltage source with a smaller value of R_i is examined?

- A real, unstabilised voltage source with an internal resistance of R_i = 3 Ω, has a source voltage of U_0 = 15 V. How large is the short circuit current I_K and what would probably happen if the output of the voltage source was inadvertently short circuited?

- Electronic circuits require a supply voltage. This voltage must not fall below a specific value, otherwise the circuit will not function correctly, or not at all. An example is the button cell in a digital wristwatch. When the cell voltage falls, the display goes off.

  Assuming that a button cell has the same values as those shown on the characteristic in Fig. 5.2.2. How would you comment on the ability of the supplied circuit to function under the following conditions?

  a. The load resistor of the circuit, R_L is 22 Ω

  b. The button cell is loaded by R_L = 680 Ω

- Assuming that a circuit supplied by a button cell, tolerates the fall in voltage that occurs in case 'a.' above, without any loss of functionality. Is a button cell suitable for supplying a voltage where the resistance of the consumer is only 22 Ω? Give reasons for your answer.

6. Interconnection of Voltage Sources

6.1 Symbols Used for Voltage Sources

DC voltage sources, the internal construction of which is of no significance, are represented by standard circuit symbols.

The symbol shown in A of Fig. 6.1.1 is used for galvanic elements, where chemical reaction is converted to electrical energy. It symbolises a **primary cell** (battery) or an **accumulator**. In contrast to primary cells, accumulators can be recharged.

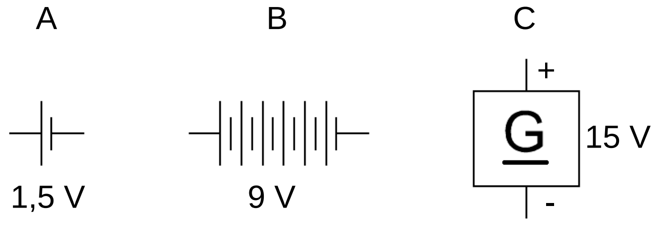


Fig. 6.1.1: Circuit symbols for voltage sources

When several primary cells are connected in series to increase the terminal voltage, the symbol shown in Fig. 6.1.1 B.

If DC voltages are generated by other forms of electrical energy, the symbol shown in Fig. 6.1.1 C is used. The 'G' stands for Generator and the line under the G indicates that a DC voltage is generated.

6.2 Series Connection of Voltage Sources

6.2.1 Properties of Series Connected Voltage Sources

When voltage sources are connected in series, the total terminal voltage is higher. The partial voltages are added only when poles with opposite polarity are connected together. In Fig. 6.2.1.1, the negative pole of source 1 is connected to the plus pole of source 2. The two poles not connected, then form the output terminals across which the load resistance R_L is connected.

When the voltages are connected correctly in series:

$$U_{tot} = U_1 + U_2 + U_3 + \ldots + U_n$$

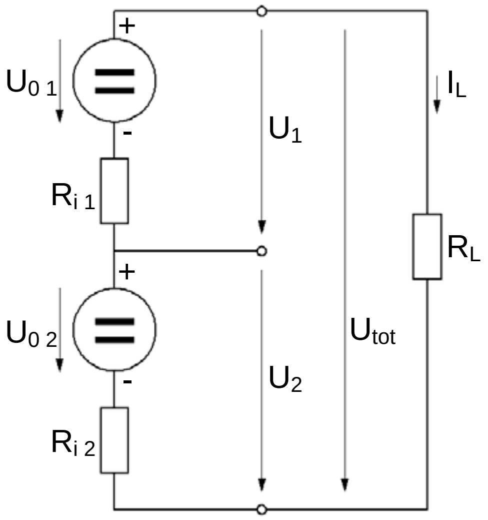


Fig. 6.2.1.1: Series connection of voltage sources

When voltage sources connected in series are operated off-load, then the total voltage U_{tot} is given by the sum of all individual source voltages, U_{0n}:

$$U_{tot} = U_{0,tot} = U_{01} + U_{02} + U_{03} + \ldots + U_{0n}$$

As to be expected in a series circuit, the internal resistances R_i add to give the total internal resistance, $R_{i\,tot}$:

$$R_{i\,tot} = R_{i1} + R_{i2} + R_{i3} + \ldots + R_{in}$$

When a consumer is connected, the load current I_L is limited by its resistance R_L and the sum of all internal resistors, $R_{i\,tot}$:

$$I_L = \frac{U_{tot}}{R_L + R_{i\,tot}} = \frac{U_1 + U_2 + U_3 + \ldots + U_n}{R_L + R_{i1} + R_{i2} + R_{i3} + \ldots + R_{in}}$$

6.2.2 Series Connection of Voltage Sources as an Exercise

One of the poles of the DC voltage sources on the Electronic Circuits Board connected together. This forms the reference point known as Ground, 'GND' (or 'earth'). In Fig. 6.2.2.1 the reference point GND, is shown between the DC voltage generators by its standard circuit symbol.

The negative pole of Source 1 (red) and the plus pole of Source 2 (blue) are connected to GND. This then gives a series circuit of both voltages when a load is connected across the 'free' poles (Fig. 6.2.2). individual voltages (U_1, U_2) add to produce the total voltage $U_{tot} = 30$ V which causes the load current I_L to flow in the consumer ($R_L = 4{,}7$ kΩ).

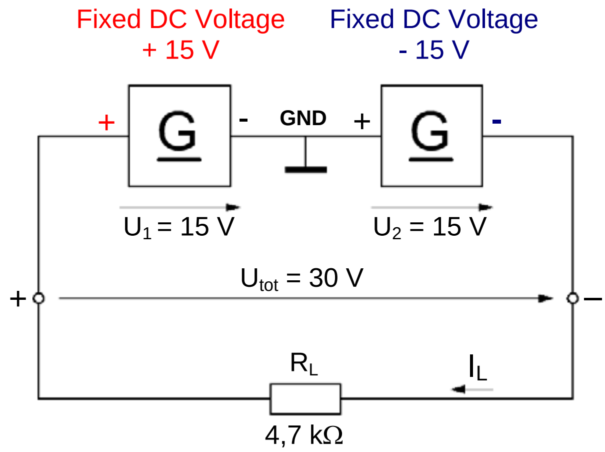


Fig. 6.2.2.1: Series circuit of 2 voltage sources

- Connect the two Fixed DC Voltage together as shown in Fig. 6.2.2. Connect a load resistor of $R_L = 4{,}7$ kΩ at the output ($U_{tot} = 30$ V) The correct assembly layout is shown in section 6.2.3.
- Switch the supply to the Board on and measure the values required to complete table 6.2.2.2.

U1 [V]	U_2 [V]	U_{tot} [V]	I_L [mA]

Table 6.2.2.2: Series circuit of voltage sources

- Calculate the actual value of load resistance, R_L.

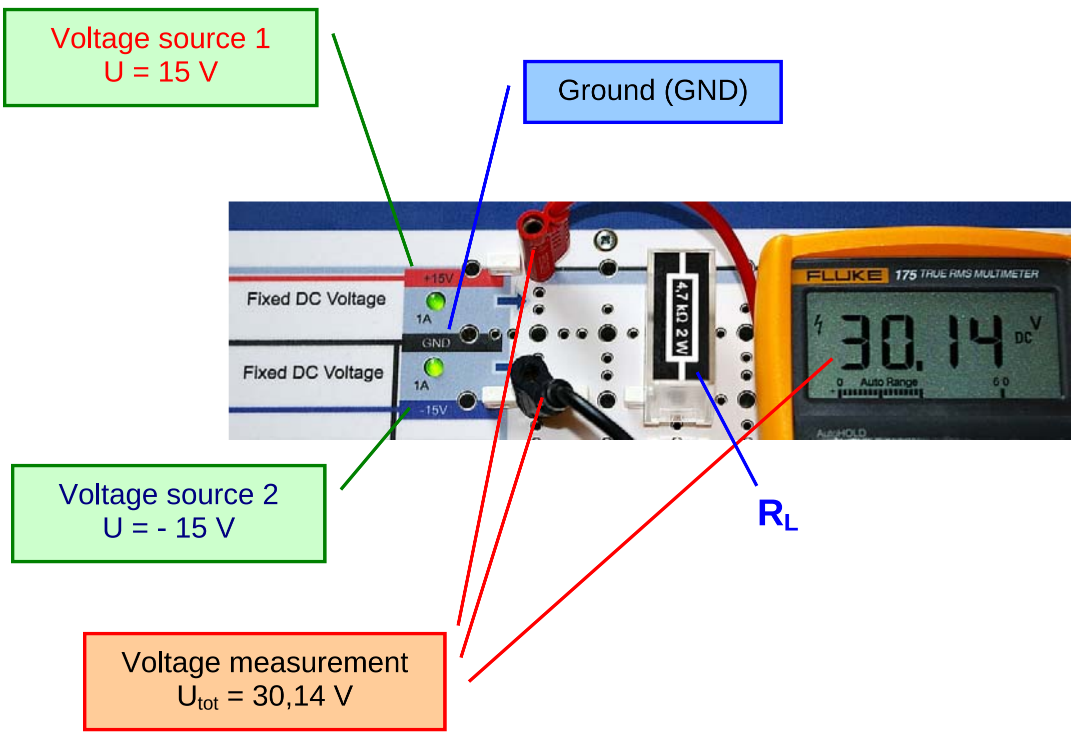
What power is dissipated at the consumer (load resistor)? What power is delivered by each individual voltage source?

- Which current direction – technical or physical – is indicated for the load current, I_L in Fig. 6.2.2.1 and why?

6.2.3 Exercise Assembly on the Electronic Circuits Board

Fig. 6.2.3.1 shows the correct method of connecting the 2 Fixed DC Voltage sources in series for addition of the individual voltage outputs.

Fig. 6.2.3.1: Series connection of 2 fixed voltage sources



6.3 Parallel Connection of Voltage Sources

6.3.1 Properties of Parallel Connected Voltage Sources

Low-resistive consumers draw a high current from a voltage supply. High currents however, produce large losses at the internal resistance of the source and in some cases, could cause a break down of the output voltage. By connecting voltage sources in parallel, the total internal resistance of the voltage sources $R_{i\,tot}$, is reduced which results in the output (terminal) voltage remaining almost constant, even with a large flow of current.

Fig. 6.3.1.1 shows that in a parallel connection, similar poles are connected together. Thus, the branch currents I_1 to I_n are added to give the load current I_L:

$$I_L = I_1 + I_2 + I_3 + \ldots + I_n$$

Basically, the output of each voltage source, U_{0n} must be the same:

$$U_{01} = U_{02} = U_{03} = \ldots = U_{0n}$$

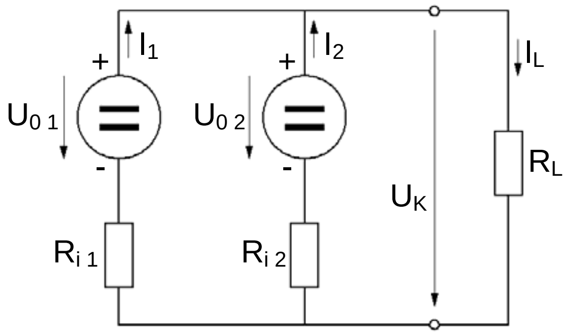


Fig. 6.3.1.1: Parallel circuit of voltage sources

If there are differences in potential, then an unwanted flow of compensating current is produced between the voltage sources. This in turn, produces internal heat losses at the internal resistance $R_{i\,n}$, even when off-load.

The familiar equation for parallel circuits can be used for calculating the total internal resistance, $R_{i\,tot}$.

Multiple parallel connection:

$$\frac{1}{R_{i\,tot}} = \frac{1}{R_{i1}} + \frac{1}{R_{i2}} + \frac{1}{R_{i3}} + \ldots + \frac{1}{R_{in}}$$

Twofold parallel connection:

$$R_{i\,tot} = \frac{R_{i1} \cdot R_{i2}}{R_{i1} + R_{i2}}$$

Identical sources:

$$R_{i\,tot} = \frac{R_i}{n}$$

6.3.2 Parallel Connection of Voltage Sources as an Exercise

Two voltage sources on the Board are connected in parallel for examining their properties by measurement. Their internal resistance will be simulated by connecting an 'external R_i' (Fig. 6.3.2.1).

- First, set the output of the Variable DC Voltage source to $U_{0\,2}$ = 15 V. Then, switch the Board off again.

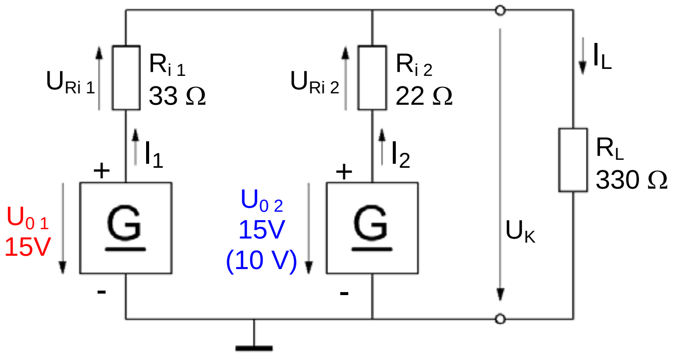


Fig. 6.3.2.1: Parallel circuit of voltage sources

- Assemble the circuit in Fig. 6.3.2.1 on the Board. Use the Fixed DC Voltage as source voltage $U_{0\,1}$ = 15 V and the Variable DC Voltage as $U_{0\,2}$ = 15 V.
- Measure the values to complete table 6.3.2.2 with equal source voltages ($U_{0\,1} = U_{0\,2}$).

$U_{0\,1} = U_{0\,2}$	$U_{Ri\,1}$ [V]	$U_{Ri\,2}$ [V]	U_K [V]	I_1 [mA]	I_2 [mA]	I_L [mA]
Off-load					X	X
R_L = 330 Ω						

Table 6.3.2.2: Measurements at parallel connected voltage sources ($U_{0\,1} = U_{0\,2}$)

- Why does a small compensating current flow between the two voltage sources when operated off-load?

- What relationship exists between the values of current measured (I_1, I_2 and I_L), when the consumer, R_L = 330 Ω is connected?

- Why are the voltage drops across the internal resistances $R_{i\,1}$ and $R_{i\,2}$ almost identical, although the current flows through each I_1 and I_2, are different?
- Calculate the total internal resistance, $R_{i\,tot}$ from the measured values in table 6.3.2.2.

- Check the calculation of total internal resistance, $R_{i\,tot}$ using the equation from section 6.3.1 and the nominal values for $R_{i\,1}$ and $R_{i\,2}$.

- Measure the terminal voltage, U_K again with a load of R_L = 330 Ω. The value obtained should correspond to the value measured in table 6.3.2.2. With the supply voltage switched on, withdraw $R_{i\,2}$ = 22 Ω from the circuit, to supply the consumer with only $U_{0\,1}$. What value is the terminal voltage U_K? Explain the change.

- Now set the source voltage $U_{0\,2}$ to 10 V. The output of the Variable DC Voltage source must remain 'open circuit'.
- Connect the two (different) voltage sources ($U_{0\,1} \neq U_{0\,2}$) in parallel as in Fig. 6.3.2.1 and measure the values to complete table 6.3.2.3.

$U_{0\,1} \neq U_{0\,2}$	$U_{Ri\,1}$ [V]	$U_{Ri\,2}$ [V]	U_K [V]	I_1 [mA]	I_2 [mA]	I_L [mA]
Off-load					X	X
R_L = 330 Ω						

Table 6.3.2.3: Measurements at parallel connected voltage sources ($U_{0\,1} \neq U_{0\,2}$)

- How can the comparatively high value for I_1 in off-load operation, be explained?

- What relationship exists between your measured values of current I_1, I_2 and I_L, when the consumer R_L = 330 Ω is connected?

- Is it appropriate to supply a consumer (e.g. an electronic circuit), from a parallel connection of two differing sources of voltage?

6.3.3 Exercise Assembly on the Electronic Circuits Board

Fig. 6.3.3.1 shows the correct method of connecting the 2 voltage sources Fixed DC Voltage and Variable DC Voltage, in a parallel circuit.

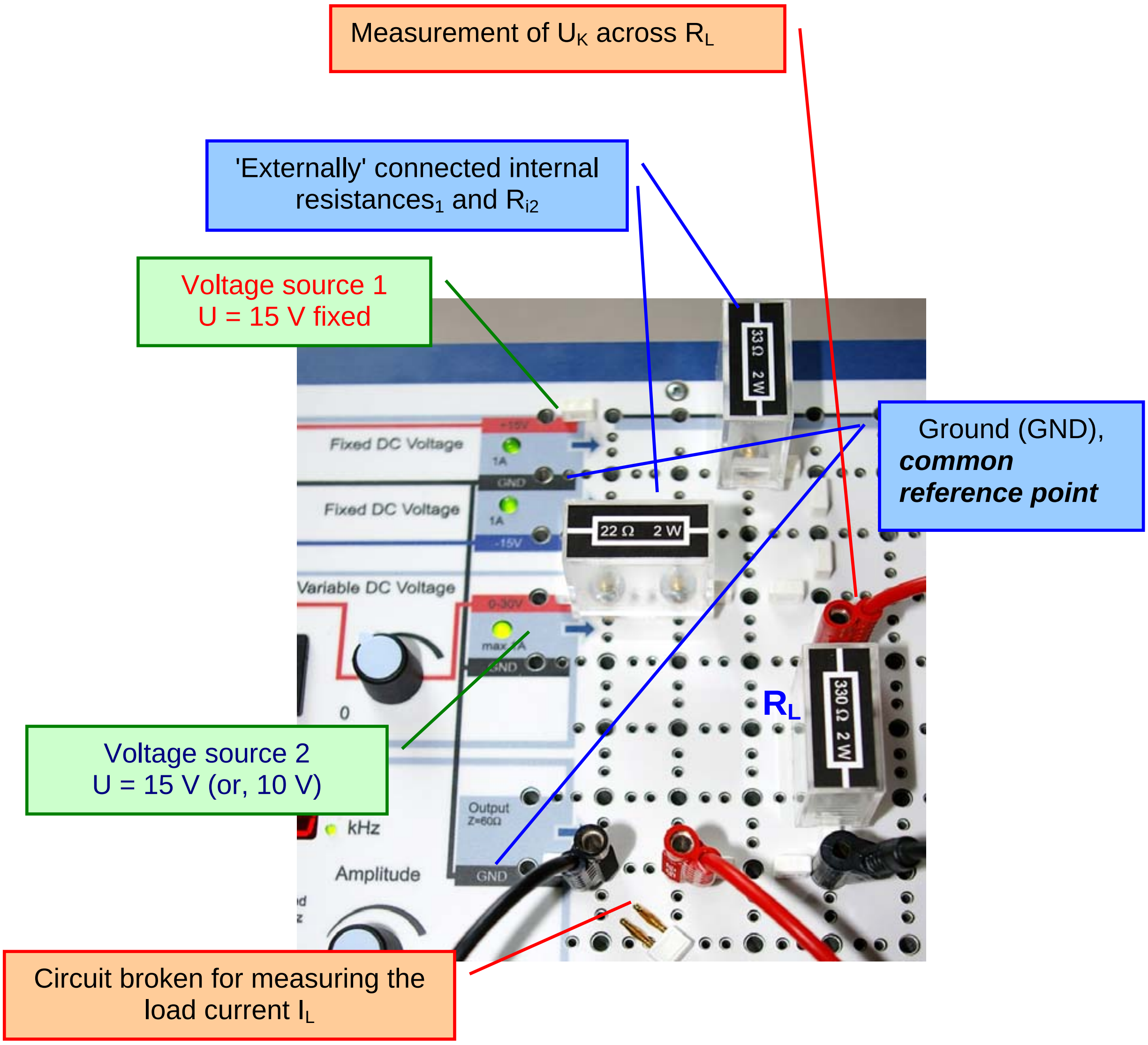


Fig. 6.3.3.1: Parallel circuit of 2 voltage sources on the Board

7. Electrical Energy and Power

7.1 Energy and Power in an Electrical Circuit

Consider the example of operating a garden pump, to pump 100 litres of underground water up to garden level. This involves a certain amount of 'work' and the 'power' invested in the work will be felt when this has been accomplished in the old-fashioned way, i.e. by mechanical means using a pump handle. Also, it is clear that the efforts involved must be sustained over a certain period of time until the amount of water required, has been pumped. Therefore, work or 'energy' can be defined as 'power' that must be available for a specified time:

$$\textit{Work} = \textit{Power} \times \textit{Time} \quad \Rightarrow \quad W = P \cdot t$$

If the pump is to be fitted with an electric drive, a voltage U, must be connected to the input terminals that will then cause a current I to flow. In electric circuits, power is calculated from the product of voltage U and current I (unit: Watt, W):

$$P = U \cdot I$$

As long as the current flows, energy is consumed, i.e. power for a specified time. Thus, the energy or work W, in an electric circuit is calculated as:

$$W = U \cdot I \cdot t$$

The unit of electrical energy or work, is the 'watt-second' (Ws) or 'kilowatt-hour (kWh = 1.000 W x 3600 s).

The electrical work consumed in a household is measured on a meter (kWh meter) and depending on existing contract agreements, must be paid for quarterly or annually. The electrical energy provider is not really interested on how this energy has been used:

- The work W can be the sum of smaller amounts, added over a long period (e.g. filament lamps).
- The same quantity of work can also result from using one consumer for a short time (e.g. an oven or electric heater).

From the examples it is clear the electric power P used for producing a certain amount of work, is usually converted to other forms of energy. Voltage and current produce movement (electric motor), sound waves (loudspeaker), light (lamps), warmth (electric heating) or cooling (refrigerator or freezer). However, when operating electric or electromechanical equipment, there are always unwanted power losses, such as the already known thermal power dissipation at resistances (P_v).

Electric power P is calculated from the known variables: $\boldsymbol{P = U \cdot I}$

or substituting current: $P = U \cdot I$ and $I = \frac{U}{R} \Rightarrow P = \frac{U}{R} \cdot U \Rightarrow \boldsymbol{P = \frac{U^2}{R}}$

or Substituting voltage: $P = U \cdot I$ and $U = R \cdot I \Rightarrow P = R \cdot I \cdot I \Rightarrow \boldsymbol{P = I^2 \cdot R}$

7.2 Practical Exercises, Power and Work in an Electric Circuit

The practical exercises following will show the relationships between the basic variables voltage U, current I, resistance R and the electric power. A series of measurements will be recorded in the circuit shown in Fig. 7.2.1 and represented in a graph. The resistor components used in the circuit, 100 Ω, 220 Ω and 330 Ω, all have a maximum power dissipation of P_v = 2 W.

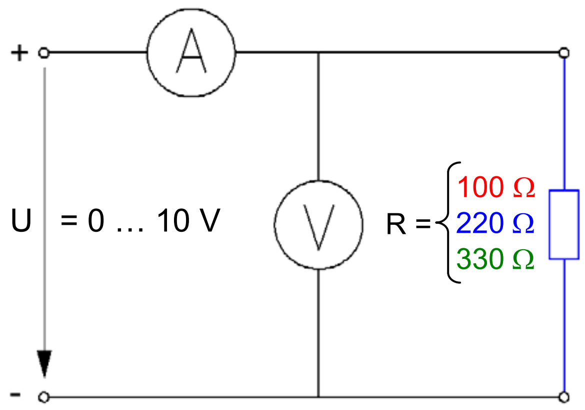


Fig. 7.2.1: Circuit with resistors

- By calculation, first ensure that the intended input voltage of U = 0 … 10 V does not exceed the maximum power dissipation of the resistors.

- Assemble the circuit in Fig. 7.2.1 on the Electronic Circuits Board for recording the measurements.
- Measure the values of current as a function of voltage and resistance. Enter the values measured in table 7.2.2.

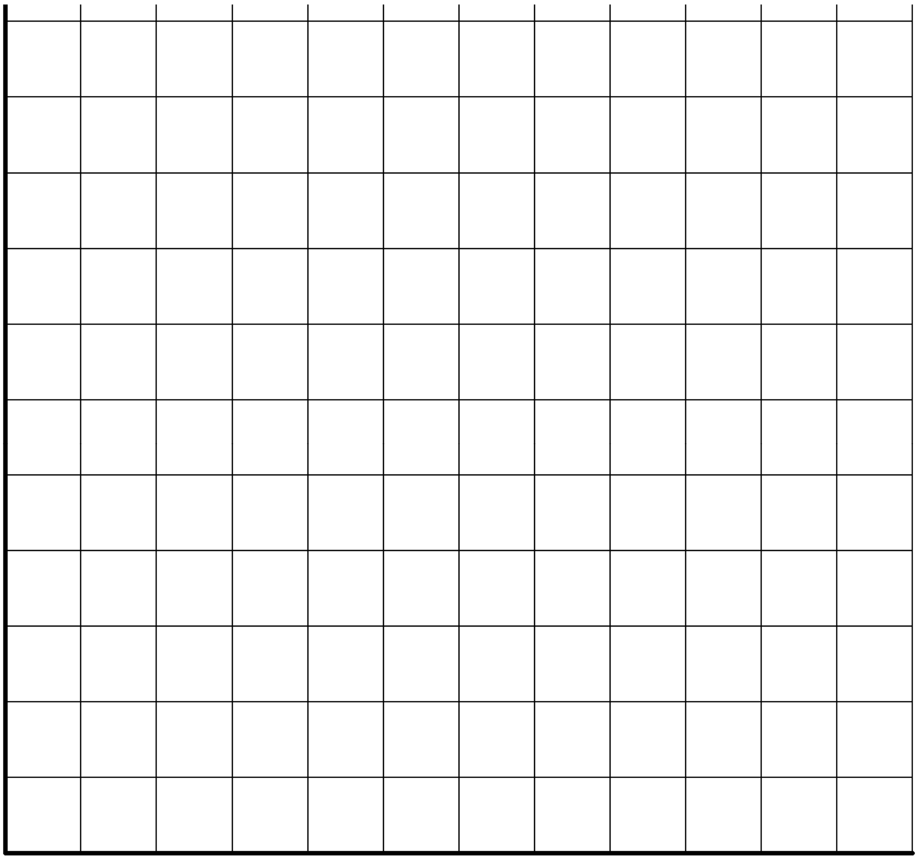
	U [V]	1	3	4	5	7	8	10
R = 100 Ω	I [mA]							
	P [mW]							
R = 220 Ω	I [mA]							
	P [mW]							
R = 330 Ω	I [mA]							
	P [mW]							

Table 7.2.2: Values measured at various resistors

- Complete the values for power P, in table 7.2.2 by calculation.
- Now, the power characteristic P = f(U) will be drawn, using the measured values from the table. What basic curve shape do you expect to produce for the characteristic? Give reasons for your answer.

- Plot the measured values in the chart (Fig. 7.2.3). draw the characteristics P = f(U) for each of the 3 resistors.

Fig. 7.2.3: Characteristics P = f(U)



- What is the significance of the parabolic shape ($y = a\,x^2$) of the characteristic for the power transformed at a consumer?

- What conclusion can be drawn from a comparison of the 3 characteristics?

- In a voltage – current graph (Fig. 7.2.5), all points corresponding to a power of 2 W are to be plotted to produce a graph ('power hyperbola'). Using the voltage values given in table 7.2.4 and a constant power of P = 2 W, calculate the current flow at each value of voltage. Which formulae should be used?

  Formula:

U [V]	2	2,5	3	3,5	5	7	9	10
I [A]								

Table 7.2.4: Voltage and current at a constant power of P = 2 W

- Plot the values of U and I in the chart (Fig. 7.2.5) and join the plotted points to produce the power hyperbola for a 2 W resistor.

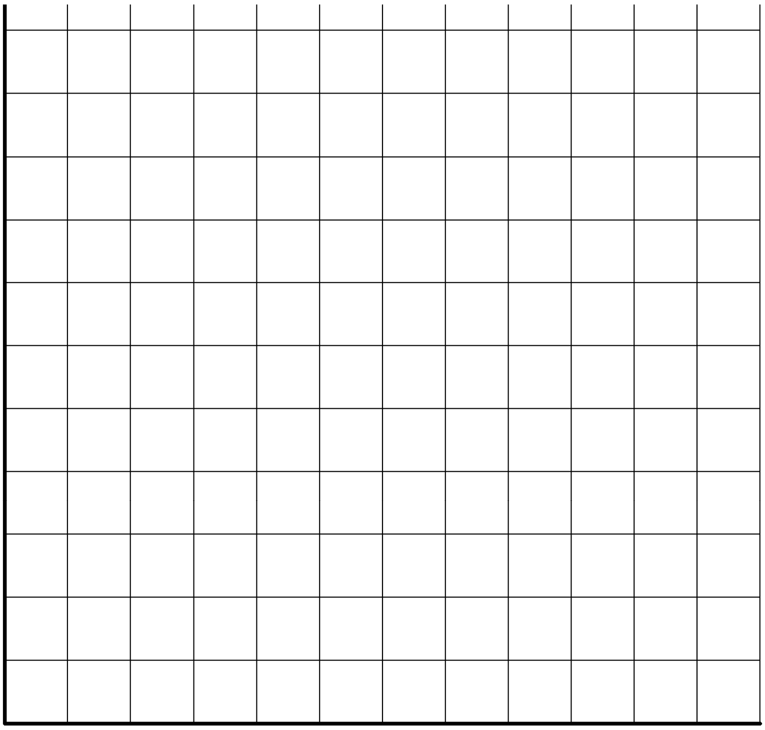


Fig. 7.2.5: Power hyperbola, 2 W

A power hyperbola graph can be used to determine the maximum permissible voltage drop at a 2 W resistor. First, the characteristic I = f(U) of the relevant resistor, must be drawn in the graph Fig. 7.2.5. The intersecting point of the resistance characteristic and the hyperbola corresponds to the maximum voltage and also shows the value of current flow.

- Draw the resistance characteristic I = f(U) for the 22 Ω resistor in the graph (Fig. 7.2.5), using 2 voltage values.

- What is the maximum value of voltage that may exist across the 22 Ω resistor on the Electronic Circuits Board, so that the maximum power dissipation (P_v = 2 W) of the component is not exceeded? Determine this value and the current flowing, from the graph in Fig. 7.2.5.

- Check the values by calculation.

- Insert a resistor of R = 22 Ω in the circuit as in the circuit, Fig. 7.2.1. Set the voltage drop across this resistor to the maximum permissible 6,63 V as accurately as possible and check that the current flow is in fact, 0,3 A.

  Assume that today is Friday and you have forgotten to switch off the Electronic Circuits Board before leaving for the weekend. How much power W in Watt-seconds [Ws] has been consumed if the voltage U_{max} = 6,63 V was switched on for exactly 3 days at the resistor R = 22 Ω?

- Convert the result to kilowatt hours [kWh].

8. Efficiency and Electrical Power

8.1 Definition and Significance of Efficiency

Energy (power) can neither be generated nor lost. Reference to energy generators means really, systems that convert one form of energy to another. For example, 'generation' of water-power to drive turbines that generate voltage. Here, the turbines first convert the potential (displacement) energy stored in the water, to torque that is then passed on the a generator. The generators transform the mechanical power to electrical power.

The electrical power obtained after this double conversion process, is not however, 100% of the original potential (displacement) energy stored in the water. Some of the energy is lost on secondary, unwanted conversion processes. For example, heat produced by friction is lost to the surrounding air, wherever there is mechanical movement. Thus, any machine, all equipment, even the biological system of the human body, suffer specific losses when 'operating' to produce some form of power.

In short, the power consumed for operating an equipment is always greater than that supplied to the User. This applies in a similar fashion to electromechanical equipment or electrical circuits. The **efficiency** of an electrical / electronic system is defined as the quotient of **delivered effective power P_{del}** and **supplied operating power P_{sup}**.

Formula: $$\eta = \frac{P_{del}}{P_{sup}}$$

P_{del} and P_{sup} in W
η = Numerical value < 1 or a percentage < 100

In the same way, the efficiency can be calculated from the ratio of delivered work to the work used.

Then, $$\eta = \frac{W_{del}}{W_{sup}}$$

W_{del} and W_{sup} in Ws
η = Numerical value < 1 or a percentage < 100

A few examples of possible efficiency:

Machine, Process, etc.	Energy applied	Useful energy	Efficiency, η
Hydroelectric power station	Potential (displacement) energy	Electrical	80 to 90 %
Coal power station	Fossil, Chemical	Electrical	25 to 50 %
Wind power station	Wind	Electrical	Up to 50 %
Filament lamp	Electric	*and* Light	3 to 5 %
Electric motor	Electric	Mechanical	20 to 99 %

Table 8.1.1: Examples of efficiency

8.2 Practical Exercises on Efficiency

An electronic circuit is supplied with a DC voltage of 7 V by way of an 8 m long cable and the same length of return cable. The cable has an ohmic resistance of R = 2 Ω per meter. Thus, the total resistance of the cable is 2 · 8 m · 2 Ω = 32 Ω. The circuit supplied by the DC voltage has an internal resistance of R_i = 680 Ω.

This application is simulated with resistors on the Electronic Circuits Board as shown in Fig. 8.2.1. The cable resistance is distributed equally along the supply and return cables. Since there are no other resistors available, the total resistance of the cable simulation (Fig. 8.2.1) is made up with 2 resistors from the E12 preferred value range.

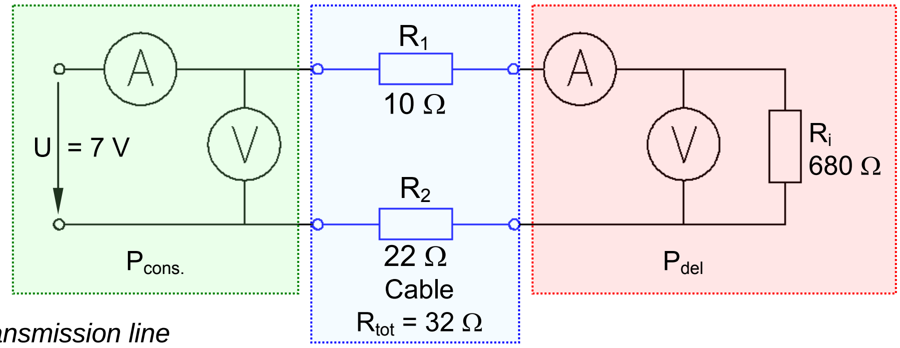


Fig. 8.2.1: Simulation of a transmission line

- Assemble the simulation circuit shown in Fig. 8.2.1 on the Electronic Circuits Board.
- Measure the values of voltage and current at the input and output terminals of the 'cable' and enter the values in table 8.2.2.

Cable input (supplied power)		**Cable output (delivered power)**	
U_{in} =	I_{in} =	U_{out} =	I_{out} =

Table 8.2.2: Values measured at the cable terminals

- From the measured values, calculate the efficiency of the transport of energy on the cable.

9. Power, Voltage and Current Matching

9.1 Derivation and Significance of Loading Conditions

In electrical and electronic circuit engineering, it is often necessary to couple standalone (independent) sections of a circuit, together. Here, the output of one circuit delivers power to the input of the next circuit.

Fig. 9.1.1: Loading on a voltage source

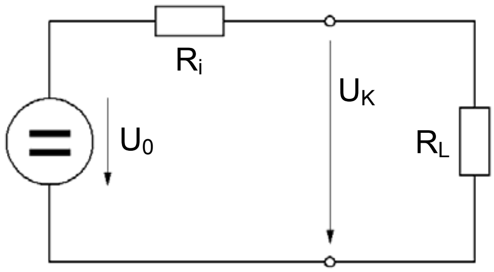


Fig. 9.1.1 shows this principle with the example of a DC voltage source that supplies a load resistor R_L. The ratio between the internal resistance R_i and the load resistor R_L determines how much of the original voltage U_0 is dropped across the load resistor R_L and is available as terminal voltage U_K. Thus, at the same time, current and power transferred are also determined. The power delivered from the voltage source, to the load resistor, is a maximum when $R_i = R_L$; the power can assume any value between maximum and zero when $R_i \neq R_L$. Two (possible, but theoretical) limiting cases will be explained here:

$R_L = \infty$; Off-load: The output terminals of a voltage source are open-circuit, i.e. no load is connected ($U_K = U_0$). The larger the load resistance compared to the internal resistance ($R_L >> R_i$), the closer are the conditions for off-load operation. In off-load operation, no power is delivered to the consumer since there is no flow of current:

$$P = U \cdot I = U_K \cdot 0 = 0$$

$R_L = 0$; Short circuit: If the output termnials of a voltage source are short-circuited with a wire bridge, the maximum possible current flows, the short-circuit current. This current is limited only by R_i. In this case, out of necessity, the terminal voltage completely collapses ($U_K = 0$), which is why no power is transferred to the consumer. The smaller the load resistance compared to the internal resistance ($R_i >> R_L$), the closer the ratio's approach the conditions of a short circuit.

$$P = U \cdot I = 0 \cdot I_{max} = 0$$

These limit cases of loading conditions, have little significance in practical circuit engineering. The matching conditions are therefore, differentiated as follows:

$R_L = R_i$; Power matching: In the case of the maximum power P, delivered to the consumer, half of the source voltage U_0 is dropped across R_L and half, across R_i.

$R_L >> R_i$; Voltage matching: A large part of the source voltage is available at the load resistance, there is a small flow of load current. This case tends towards the conditions for an off-load state ($R_L \to \infty$).

$R_L << R_i$; Current matching: The consumer draws a relatively high current from the voltage supply. The terminal voltage falls to less than half of the source voltage. Current matching tends towards the conditions of the short-circuit ($R_L \to 0$).

9.2 Practical Exercises for Loading Conditions

Power, voltage and current matching, also the limit cases of short circuit and off-load, should be examined by way of the characteristic at the consumer. Of particular importance, is to show by measurements, that with power matching when $R_L = R_i$, the highest amount of power is delivered to the consumer.

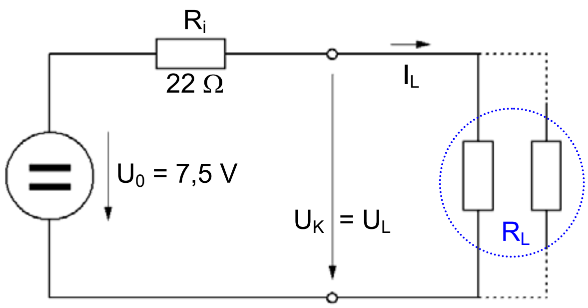


Fig. 9.2.1: Voltage source with consumer

Since the voltage sources on the Electronic Circuits Board all incorporate voltage stabilisation (R_i = 0 Ω), an internal resistance of R_i = 22 Ω will be simulated by an external resistor (Fig. 9.2.1). The load R_L is formed with individual resistors, in both a series and parallel circuit (Fig. 9.2.1 and Table 9.2.2).

- Calculate the equivalent resistance values for the series and parallel circuits and enter the values in table 9.2.2.
- Have the following values of resistor to hand: 10 Ω , 2 x 22 Ω, 33 Ω, 100 Ω, 220 Ω. Assemble the circuit in Fig. 9.2.1 on the Electronic Circuits Board.
- Start the series of measurements with the limit values 'off-load', i.e. with open circuit output terminals at the voltage source.
- Measure the load current I_L and terminal voltage U_K for each of the loading conditions (R_L). given in table 9.2.2. Enter the measured values in the table.

					Series 10+33 Ω	Parallel 100//220 Ω		
R_L [Ω]	**0**	**10**	**22**	**33**			**100**	∞
I_L [mA]								
U_K [V]								
P [mW]								

Table 9.2.2: Measurements for determining the power matching

- From the measured values, calculate power delivered P to each consumer (R_L). Enter the measured values in the table.
- Using the measured values, draw the characteristics I_L = f (R_L), $U_{L\,(K)}$ = f (R_L) and P = f (R_L) in the chart (Fig. 9.2.3).