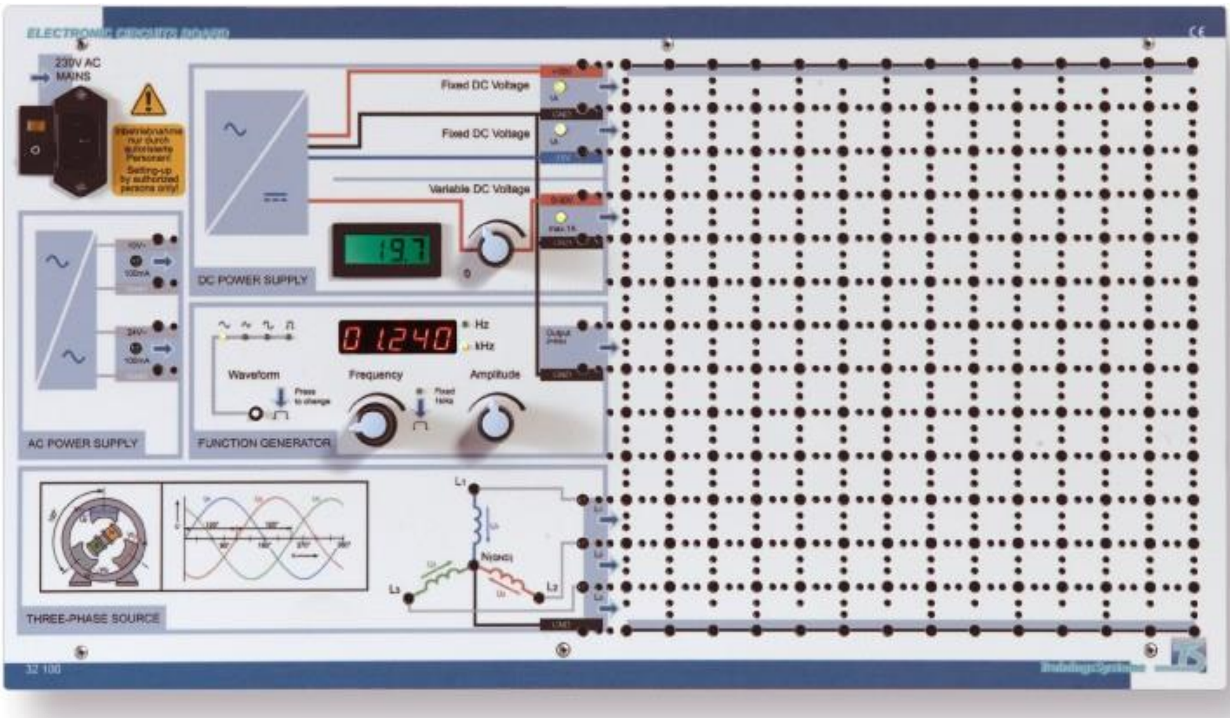
DC and AC Technology



Practical Experiments

Version 4.2 – Order No. E32 104

Contents

Experiment (1)

1. Ohm's Law

1.1 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'.

1.2 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. 1.2.1). 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.**

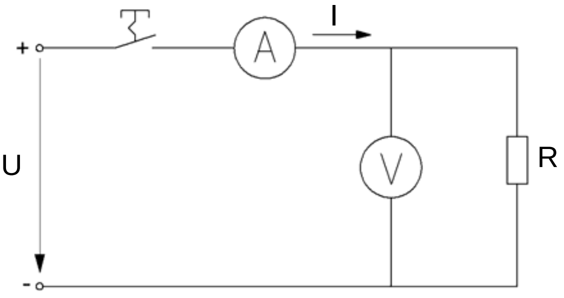


Fig. 1.2.1: Practical exercise for Ohm's law

- **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.

1.2.1 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 1.2.1.1 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							

Table1.2.1.1: I = f (U)

- Replace the resistor with one of R = 220 Ω. Repeat the series of measurements and complete table 1.2.1.1, accordingly. After completion, set the switches on the Board and circuit to OFF!
- Plot both series of measured values in the chart below (Fig. 1.2.1.2) and join the points plotted to produce a characteristic for each resistor.

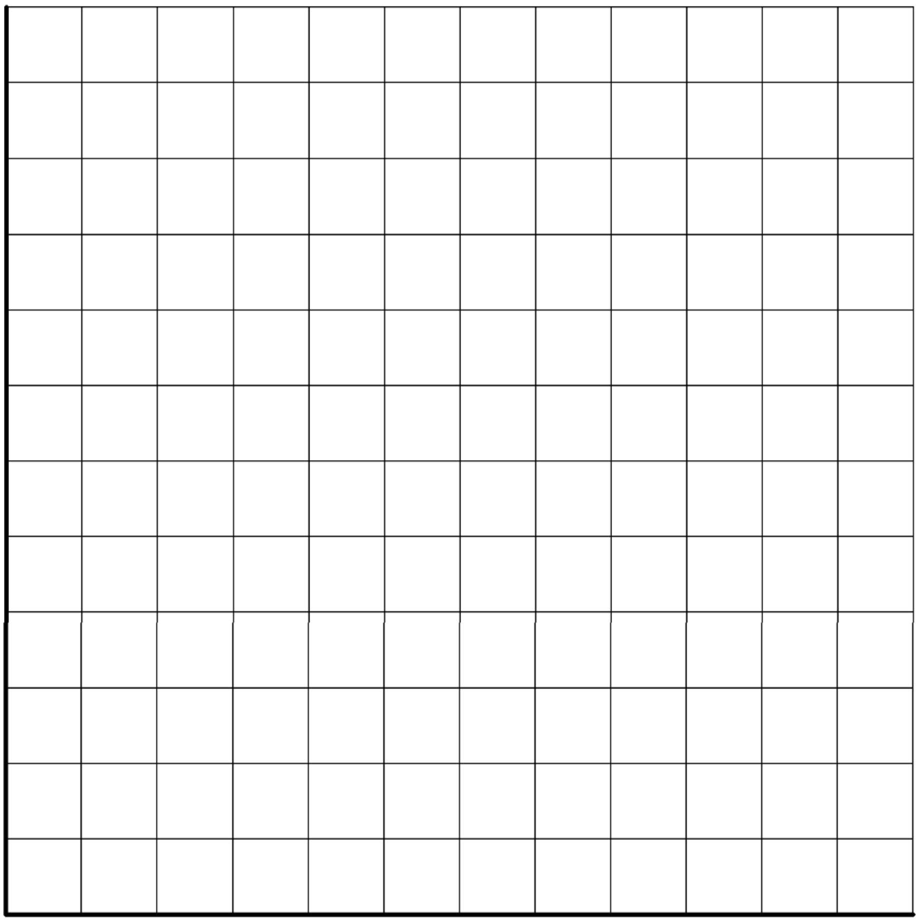


Fig. 1.2.1.2: Graph I = f (U)

1.2.2 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 1.2.2 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 1.2.2.1.
- 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 1.2.2.1: 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 1.2.2.1.
- Plot the values from the table in the chart given here (Fig. 1.2.2.2).
- Draw the characteristics I = f (R) for both voltages.

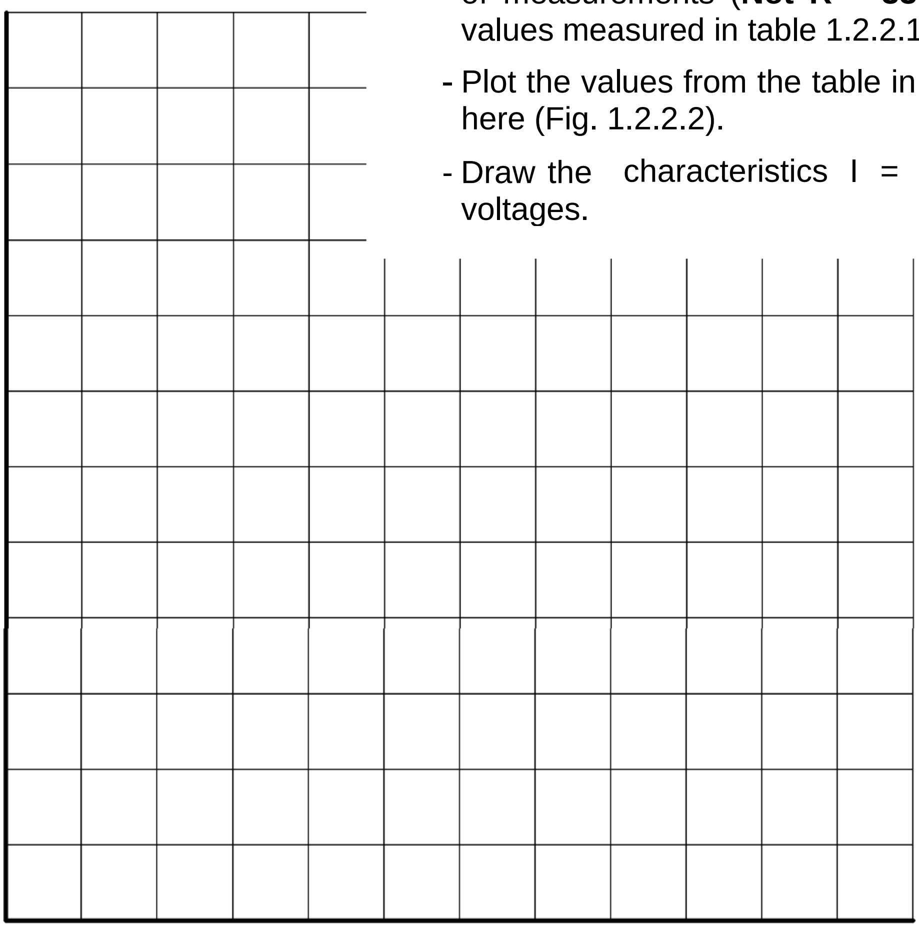


Fig. 1.2.2.2: Diagram I = f (R)

1.3 Tasks / Questions

- Calculate the current I, flowing through the resistor R, shown in Fig. 1.3.1, when the switch is closed.

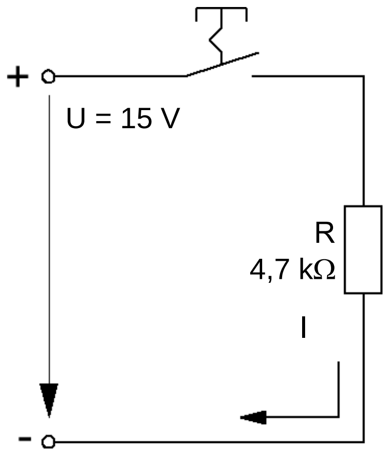


Fig. 1.3.1: Task for Ohm's law

- 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:

1.4 Exercise Assembly on the Electronic Circuits Board

Fig. 1.4.1 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. 1.4.1 have a rating limit of 2 Watt.

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

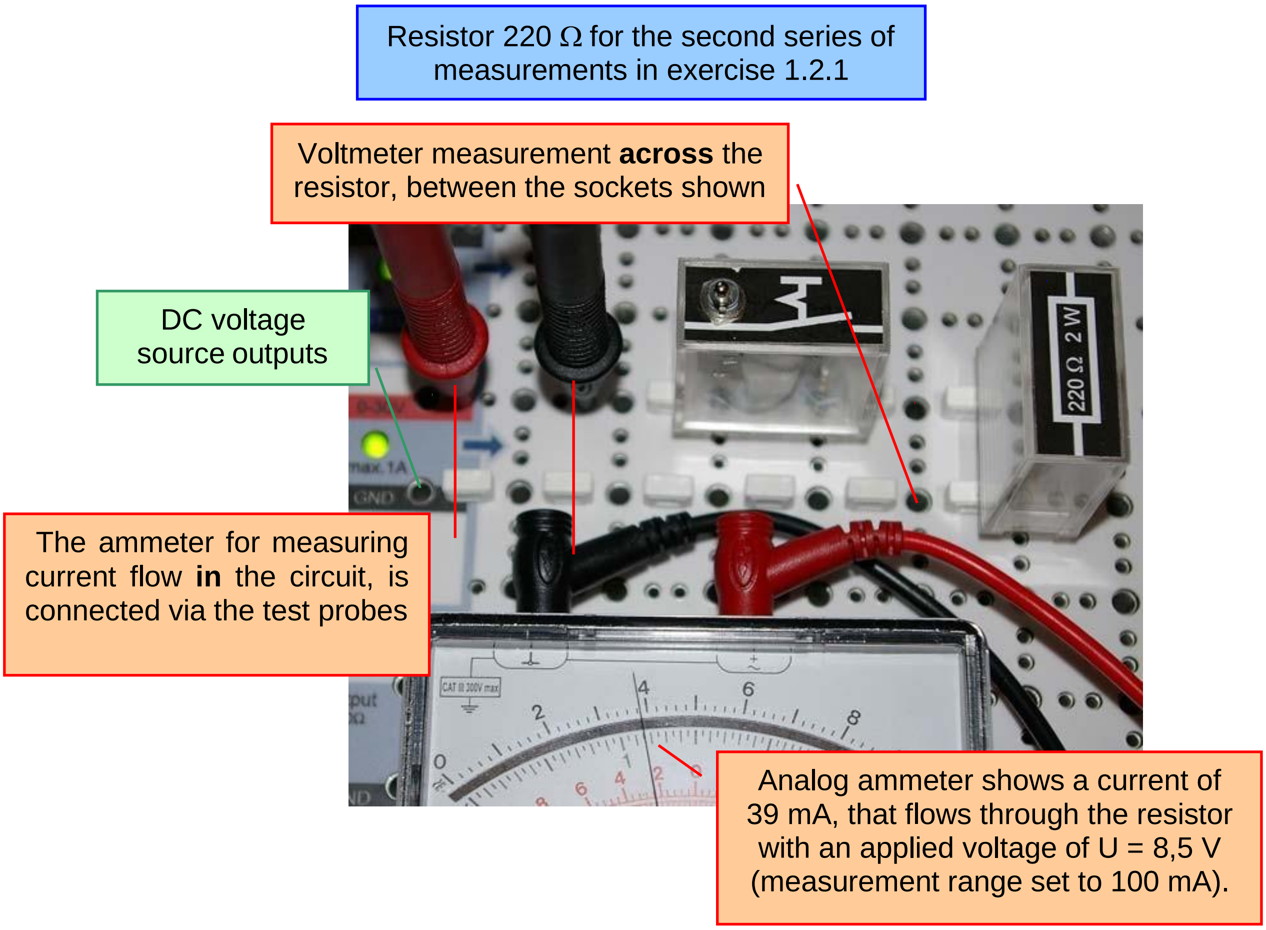


Fig. 1.4.1: Test assembly for the exercises on “Ohm's law”

1.5 Electrical Resistance

1.5 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 ratingindicates 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. 1.5.1 shows an example.

Fig. 1.5.1: 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:

$$R_{Line} = \frac{\rho \cdot l}{A}$$

ρ [Ωmm²/m]
l [mm]
A [mm²]

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.

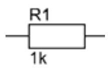
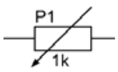
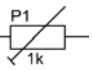
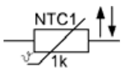
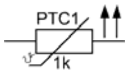
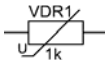
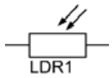
	Property	Description	Symbol
Linear	Fixed value	Resistor	
	Variable	Potentiometer, Trimmer	 
Non-linear	Temperature dependent	NTC thermistor	
		PTC thermistor	
	Voltage dependent	Varistor	
	Light sensitive	Photoresistor (LDR)	

Table 1.5.2: Linear and non-linear resistors

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

1.6 Linear Resistors

1.6.1 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.

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.

1.6.2 Recording the Characteristic I = f (U)

- **Set the main switch on the Electronic Circuits Board to OFF!**
- Assemble the exercise on the Board (Fig. 1.6.1.1). 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.

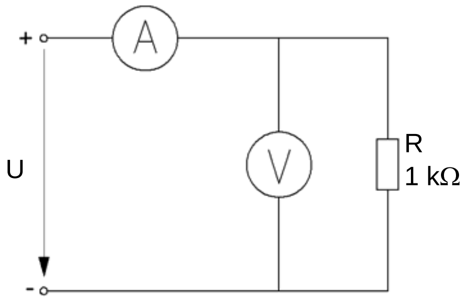


Fig. 1.6.1.1: Recording the characteristic I = f (U)

- For recording the characteristic, set the voltage values as shown in table 1.6.1.2 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 1.6.1.2: Recording the characteristic I = f (U)

- Plot the values measured for the first resistor in the chart (Fig. 1.6.1.2) and draw the characteristic of the resistor, R = 1 kΩ.

- Repeat the series of measurements with the resistor R = 4,7 kΩ. Complete table 1.6.1.2, accordingly.
- Plot the values measured for the second resistor in the chart (Fig. 1.6.1.2) and draw the characteristic, I = f (U).

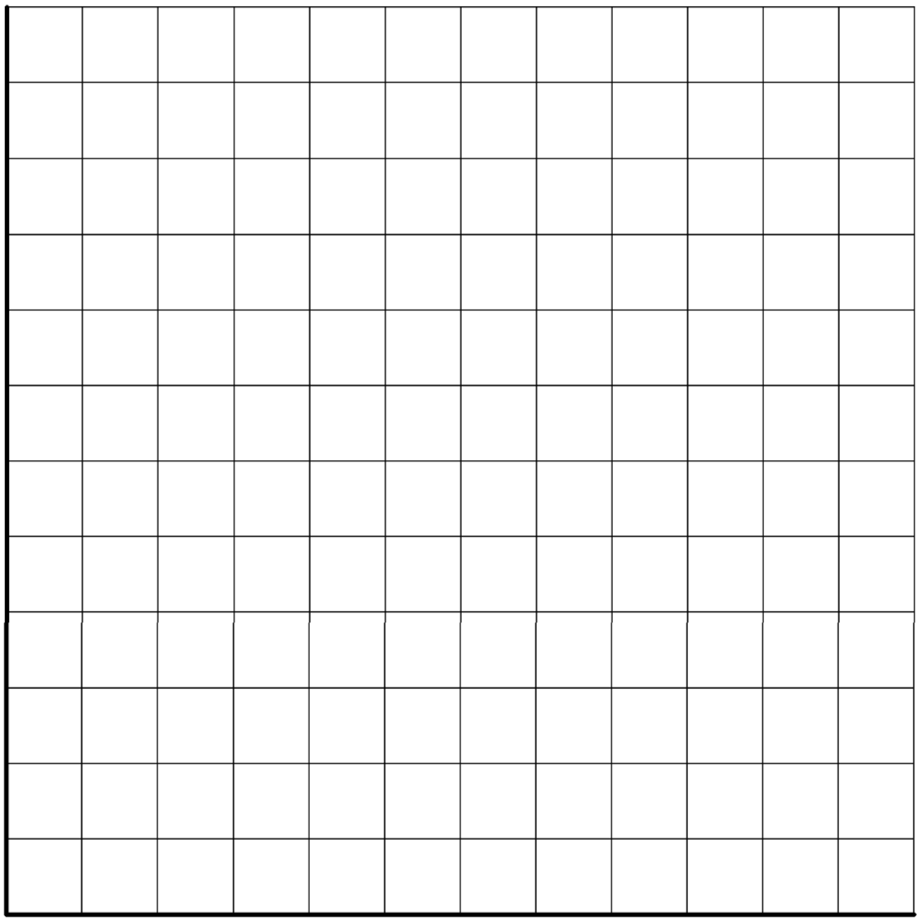


Fig. 1.6.1.2: Characteristics I = f (U)

- Using your measured values, calculate the power P, converted to heat for both resistors. Enter the calculated values in table 1.6.1.2.

  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 1.6.1.2

  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.

Experiment (2)

2. Non- linear Resistance

2.1 The NTC Resistor- 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 whenthe 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.

2.1.1 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. 2.1.1.1).

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 2.1.1.2, in sequence commencing with 5 V.
- After setting each voltage, wait a fewminutes until the current flow has stabilised. Then, measure the current and enter the values measured in table 2.1.1.2.

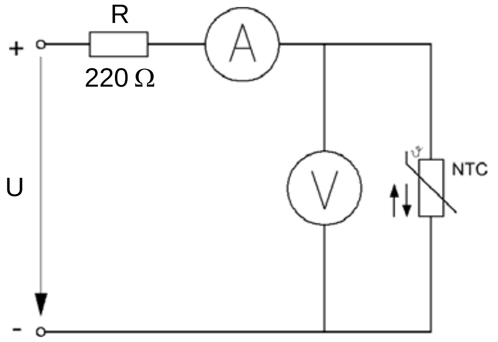


Fig. 2.1.1.1: Characteristic recording I = f (U) and R = f (U)

- **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 2.1.1.2: 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 2.1.1.2.
- Plot the values of current measured in the chart (Fig. 2.1.1.3) and join the points to give the characteristic I = f (U).
- Also, plot the values of U and R in the chart (Fig. 2.1.1.3). 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).

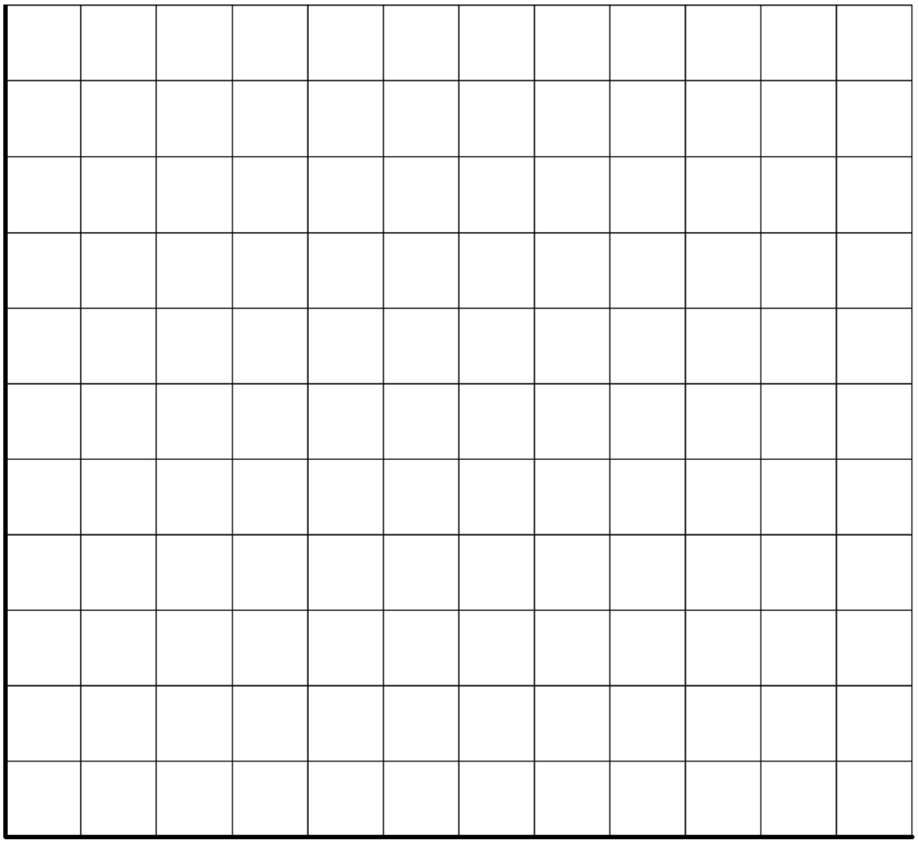


Fig. 2.1.1.3: Characteristics I = f (U) and R = f (U) for the NTC resistor at room temperature

- Break the circuit in Fig. *2.1.1.1* 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.

2.2 The PTC Resistor

2.2.1 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.

2.2.2 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.

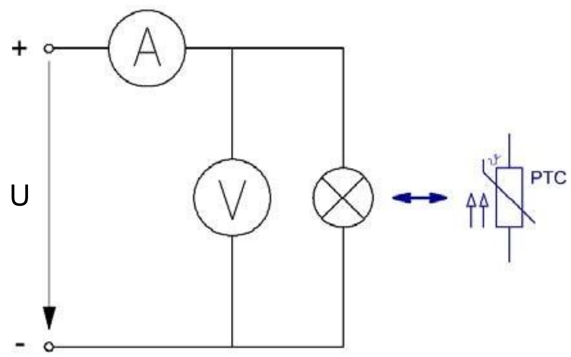


Fig. 2.2.2.1: Characteristic recording I = f (U) and R = f (U)

- Assemble the exercise circuit on the Board (Fig. *2.2.2.1*).
- For recording the characteristics, set the voltage values as shown in table 2.2.2.2, in sequence commencing with 0 V. At each voltage setting, measure the current and complete table 2.2.2.2.

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 2.2.2.2: 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 2.2.2.2.
- Draw the characteristics I = f (U) and R = f (U) in the chart (Fig. 2.2.2.3).

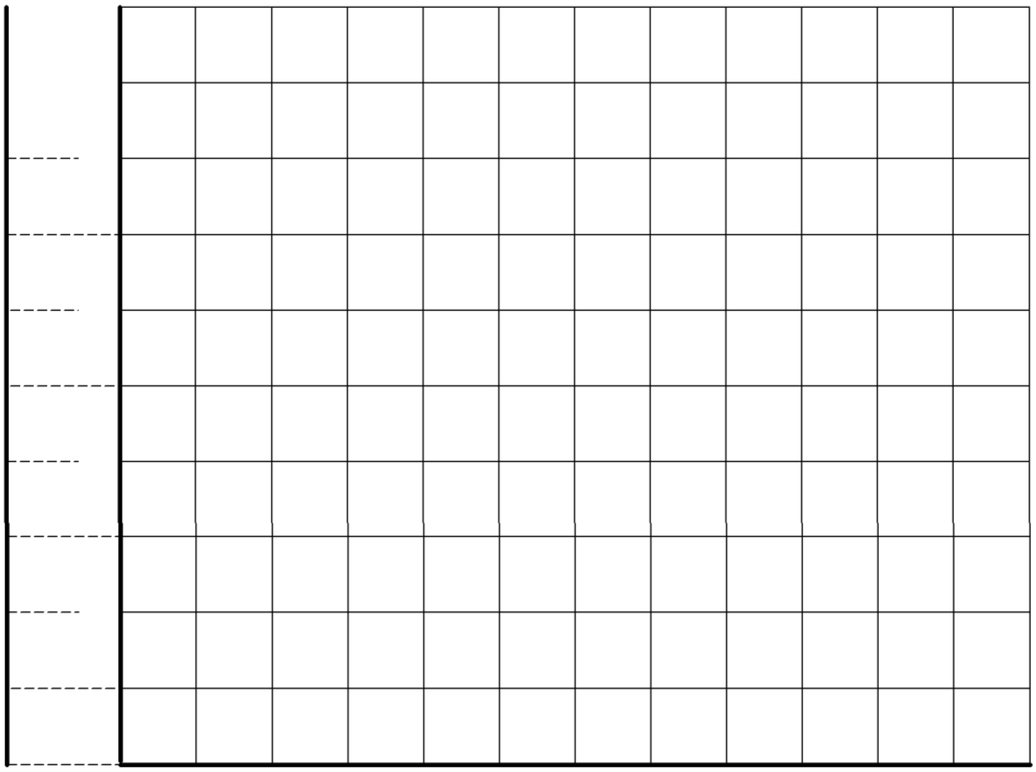


Fig. 2.2.2.3: Characteristics, I = f (U) and R = f (U) of the PTC resistor ('lamp')

- 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?

2.3 Voltage Dependent Resistor (VDR)

2.3.1 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 stabilizing). 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.

2.3.2 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. 2.3.2.1.)

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. 2.3.2.2, in sequence commencing with 13 V.
- At each voltage setting, measure the current and complete table. 2.3.2.2.

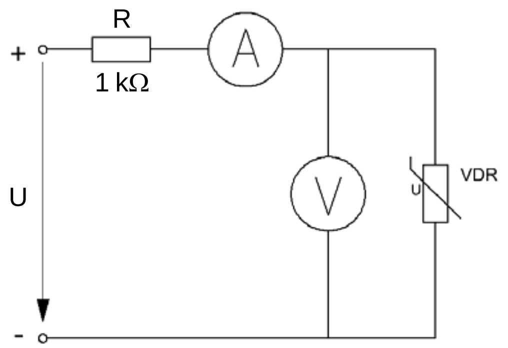


Fig. 2.3.2.1: Characteristic recording I = f (U) and R = f (U)

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. 2.3.2.2: 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. 2.3.2.3) 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. 2.3.2.3) and draw the characteristic R = f (U) by joining the points plotted.

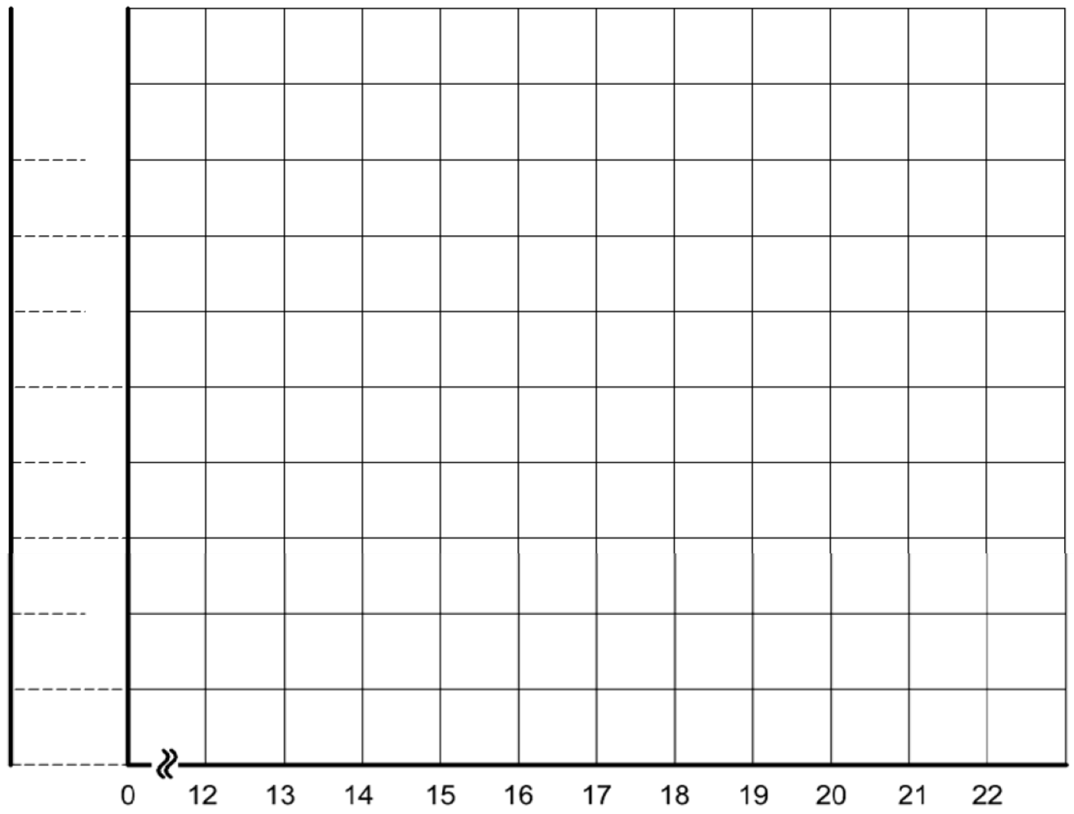


Fig. 2.3.2.3: Characteristics, I = f (U) and R = f (U) of the VDR

- 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.

2.4 Photoresistor (LDR)

2.4.1 Properties of an LDR

LDR = <u>L</u>ight <u>D</u>ependent <u>R</u>esistor

Commonly referred to, as an LDR

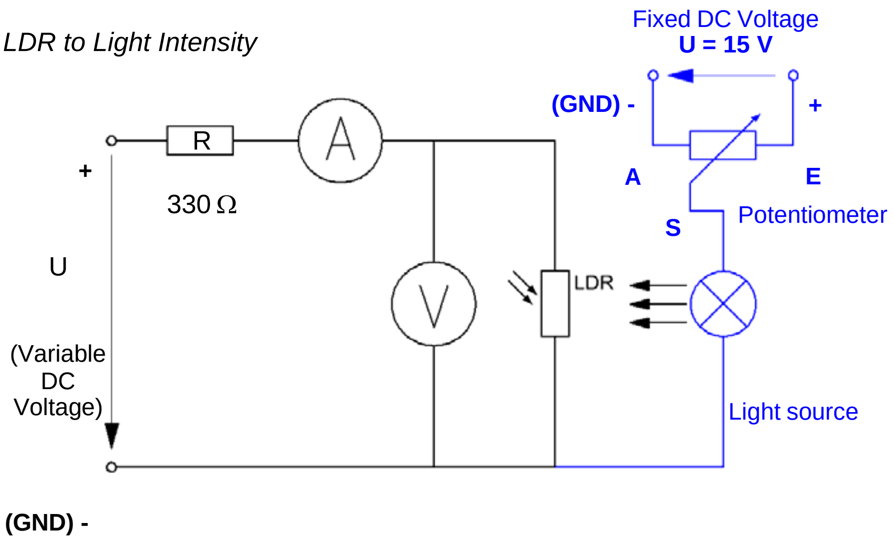
Photoresistors reduce in value when the intensity of incident light increases. They are used wherever a change in light intensity is to be detected and used as a signal in electronic circuits. For example, in light barriers, fire detectors, twilight switches, just to name a few.
A LDR is manufactured 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.

2.4.2 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. 2.4.2.1).

Fig. 2.4.2.1: 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 2.4.3.

- 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 2.4.2.2.

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

Table 2.4.2.2: Response of the LDR to Light Intensity

- Set the potentiometer to the scale values given in table 2.4.2.2. At each setting, measure the current and voltage at the LDR and enter the values in table 2.4.2.2.
- Calculate the resistance value of the LDR at the various levels of light intensity. Complete table 2.4.2.2with 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 2.4.2.2, 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?

2.4.3 Exercise Assembly on the Electronic Circuits Board

Fig. 2.4.3.1 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.

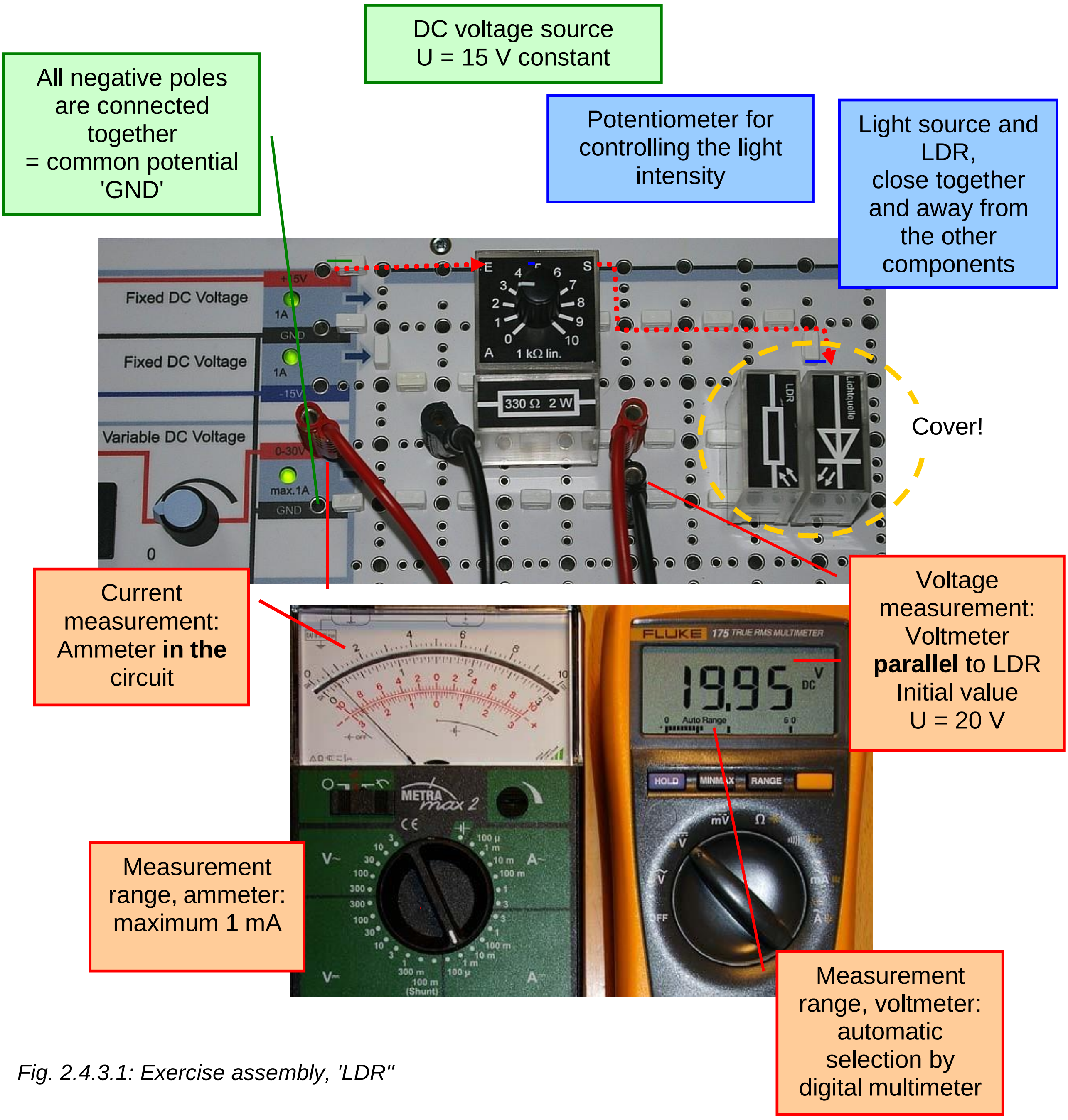


Fig. 2.4.3.1: Exercise assembly, 'LDR"

Experiment (3)

3. Connection of Resistors

3.1 Series Connection of Resistors

3.1.1 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: $U = U_{tot} + U_{R1} + U_{R2} + U_{R3} +. \quad + U_{Rn}$

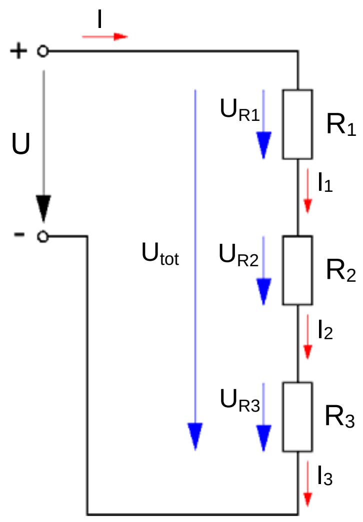


Fig. 3.1.1.1: Series circuit

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. 3.1.1.1, 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'**:

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

3.1.2 Proving the Properties of a Series Circuit of Resistors

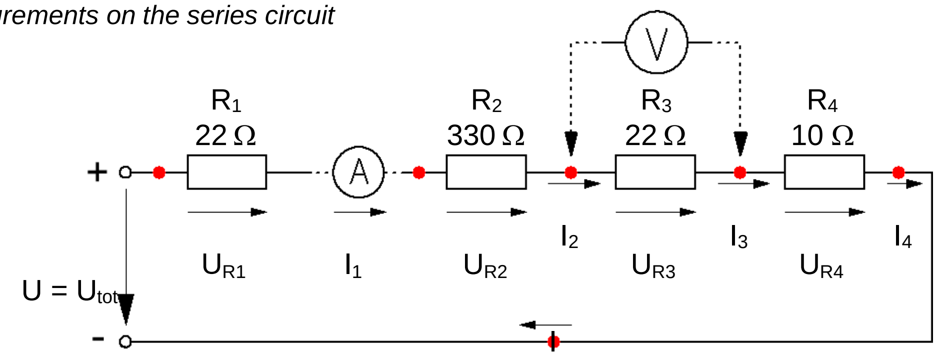
It is to be shown by measurements, that in a series connection of resistors: -

… 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. 3.1.2.1).
- 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 3.1.4, details are given on how to modify the circuit with a minimum of re-plugging.

Fig. 3.1.2.1: Measurements on the series circuit



- First, check on the voltmeter that the input voltage is 15 V. Enter the value in table 3.1.2.2.
- 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 3.1.2.2: Measured values, Series circuit

- Measure the partial voltages across the resistors R_1 to R_4. Enter the values measured in table 3.1.2.2.
- 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.

3.1.3 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. 3.1.2.1. Verify this, using only **one** calculation.

  Result:

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

- In the circuit in Fig. 3.1.2.1, 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. 3.1.3.1, 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. Determineby calculation, the values of: R_{NTC}, R_{tot}, U_{NTC}, U_{RS}.

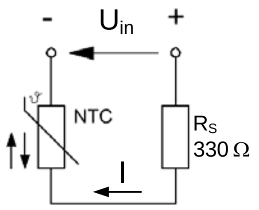


Fig. 3.1.3.1: Series circuit with NTC

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

3.1.4 Exercise Assembly on the Electronic Circuits Board

Fig. 3.1.4.1 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.

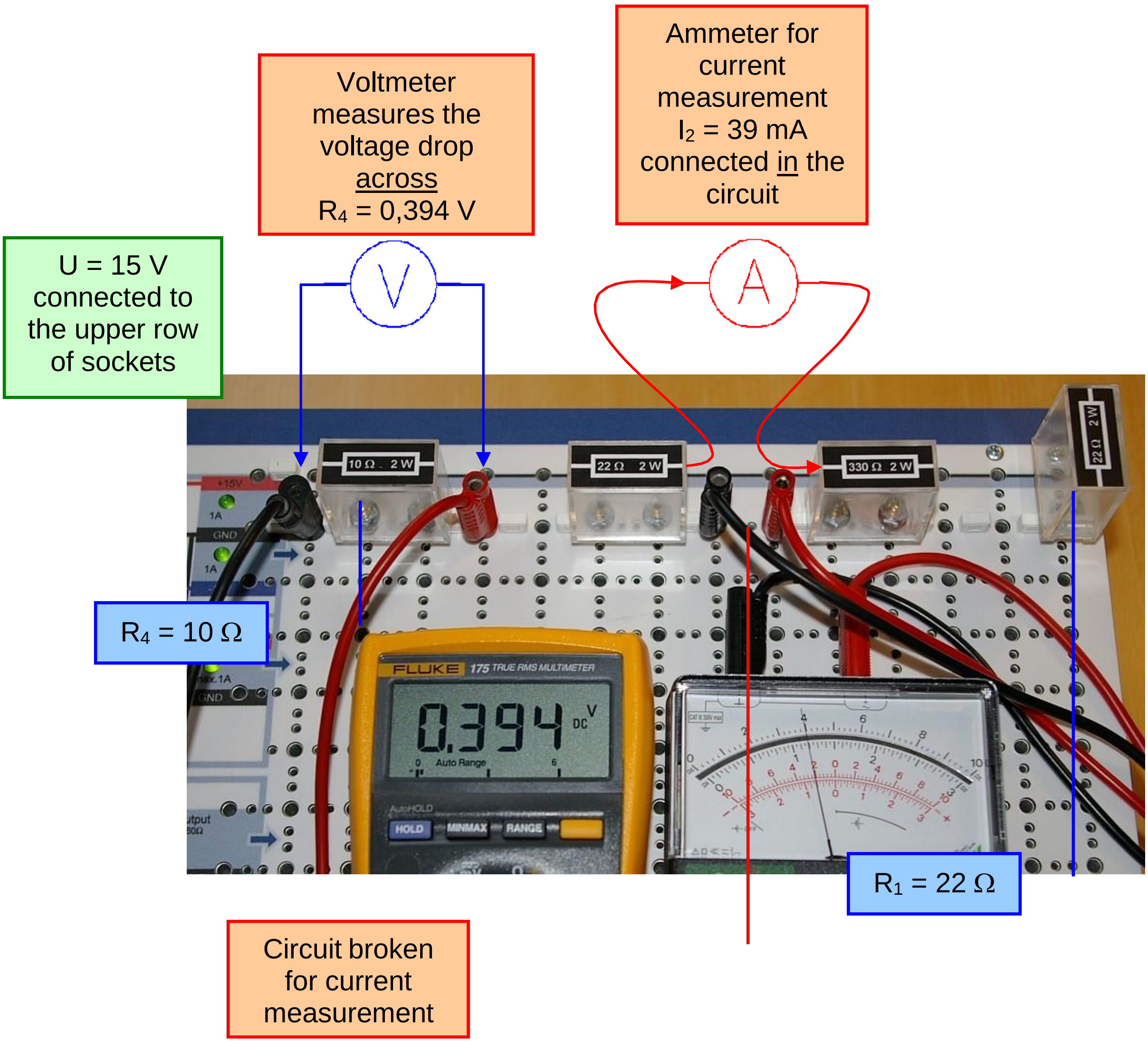


Fig. 3.1.4.1: Exercise layout, 'Series circuit of 4 resistors'

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3.2 Parallel Connection of Resistors

3.2.1 Properties of a Parallel Circuit

The same voltage is effective across

each individual resistor in a parallel circuit as in Fig. 3.2.1.1. All upperends of the resistors are connectedto plus and all lower ends, to the negative pole of the input voltage.

Therefore, it applies:

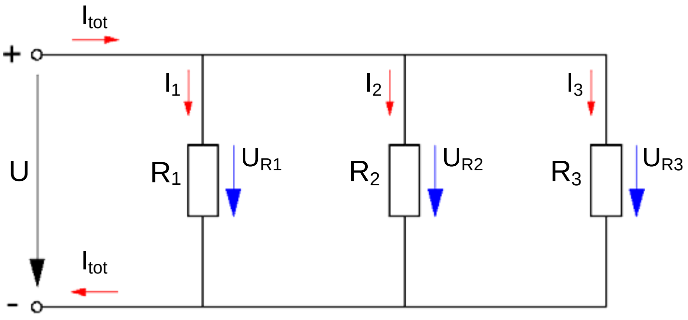


Fig. 3.2.1.1: Parallel circuit of resistors

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

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}:

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

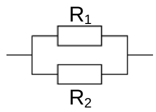
The current, I_{tot} flowing from the plus pole of the input voltage is divided through the individual resistors. Thus the term, **'voltage divider'**. If a resistor is connected inparallel to an existing resistor, the current finds an extra path for a charge carrier balance between the poles of the 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. 3.2.1.2 should clarify this statement and Fig. 3.2.1.1 from the current arrows at the side of the resistors.

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

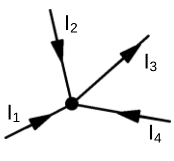


Fig. 3.2.1.2: Kirchhoff's first law

3.2.2 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. 3.2.2.1).
- 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.)

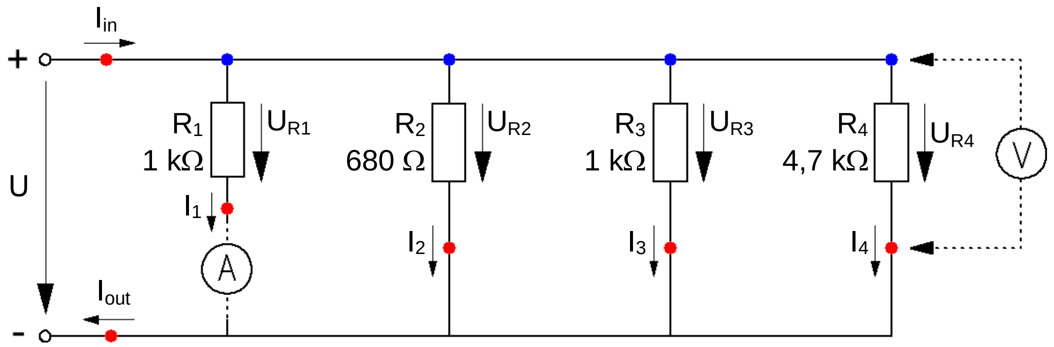


Fig. 3.2.2.1: Measurements on the parallel circuit

- First, check on the voltmeter that the input voltage is 15 V. Enter the value in table 3.2.2.2.
- 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 3.2.2.2: Measured values, Parallel circuit

- Measure the branch currents in the resistor branches R_1 to R_4. Enter the values measured in table 3.2.2.2.
- Measure the total current, I_{tot} before the resistors (I_{in}) and after (I_{out}). Complete table 3.2.2.2.

3.2.3 Tasks / Questions

- Explain the results of your voltage measurements U and U_{R1} to U_{R4} with a summarizing 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. 3.2.3.1).

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

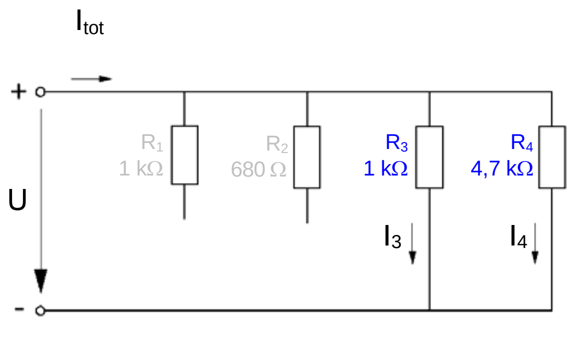


Fig. 3.2.3.1: Two resistors in parallel

- 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 parallelcircuit of Fig. 3.2.3.2 with a single resistor?

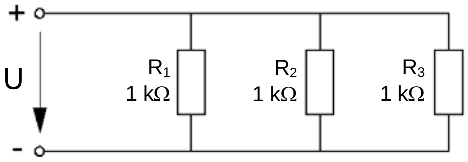


Fig. 3.2.3.2: Parallel circuit of three 1 kΩ resistors

- What is the power dissipation of the circuit in Fig. 3.2.3.2, when the input voltage applied is 15 V? For the calculation, use only voltage and resistance.

- Assemble the circuit of Fig. 3.2.3.2 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?

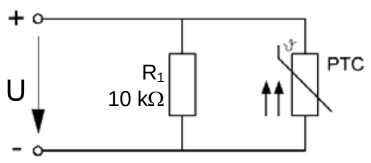


Fig.: 3.2.3.3: Parallel circuit of PTC and 10 kΩ resistor

3.2.4 Exercise Assembly on the Electronic Circuits Board

Fig. 3.2.4.1 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.

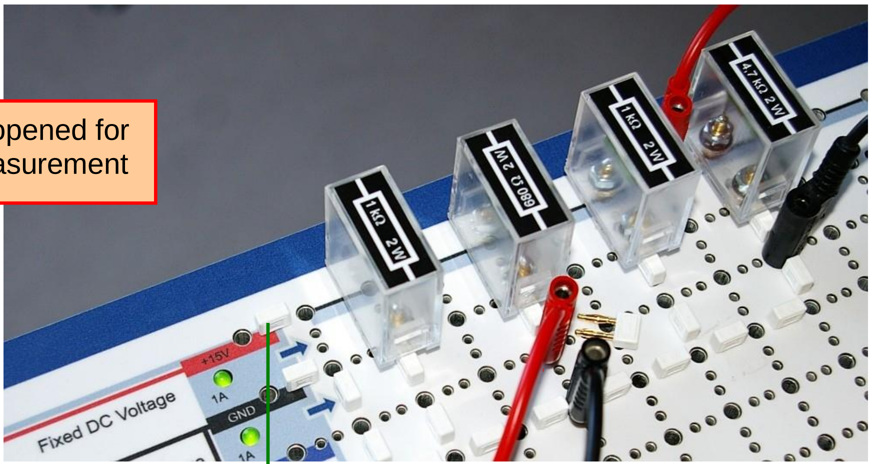


Fig. 3.2.4.1: Exercise assembly, Parallel circuit of 4 resistors

3.3 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. 3.3.1.1.

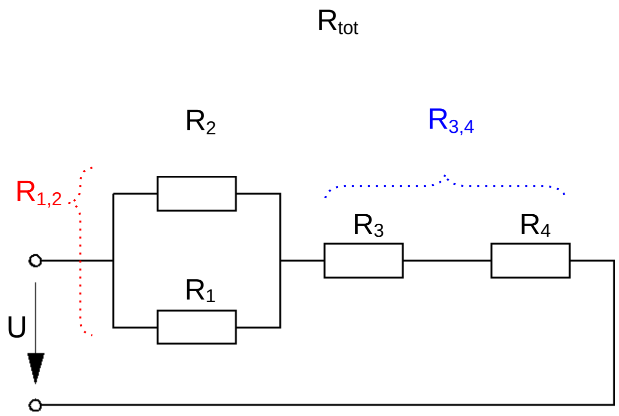


Fig. 3.3.1.1: Combination of series and parallel circuits

3.3.3 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.

For example, if the total resistance of the circuit in Fig. 3.3.1.1 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

3.3.4 Practical Exercises with Mixed Resistor Circuits

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

Resistor network 1

- Assemble the circuit of Fig. 3.3.4.1 on theElectronic Circuits Board. Ensure that it will bepossible to open the circuit at the locations required for current measurements (assembly notes will be found in section 3.3.6).

- Set the voltage at the input of the circuit, toU = 28 V. (Check the value on the multimeter and enter the value in table 3.3.4.2.

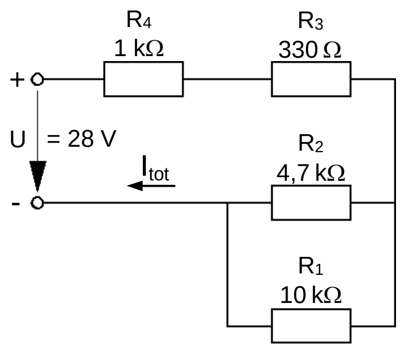


Fig. 3.3.4.1: Resistor network 1

- Measure the voltages and currents and enter the values in table 3.3.4.2.

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

Table 3.3.4.2: 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 3.3.4.2. Explain any deviations.

<u>Resistor network 2</u>

- Assemble the circuit of Fig. 3.3.4.3 on theElectronic Circuits Board. Ensure that all measurement points for voltage and current, are easily accessible (assembly notes will be found in section 3.3.6).

- Set the voltage at the input of the circuit, toU = 18 V. (Check the value on the multimeter and enter the value in table 3.3.4.4).

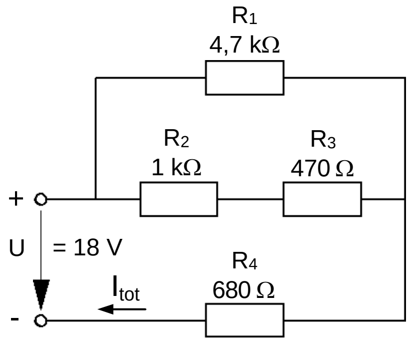


Fig. 3.3.4.3: Resistor network 2

- Measure the voltages and currents and enter the values in table 3.3.4.4.

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

Table 3.3.4.4: 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 3.3.4.4.

3.3.5 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. *3.3.4.1* is damaged (high resistance)

- How large does R_{tot} become (Fig. *3.3.4.1*), when R_2 is bridged with a piece of wire?

- In which direction does the total current I_{tot} in the circuit of Fig. 3.3.4.3 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. 3.3.4.3?

Fig. 3.3.5.1 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.

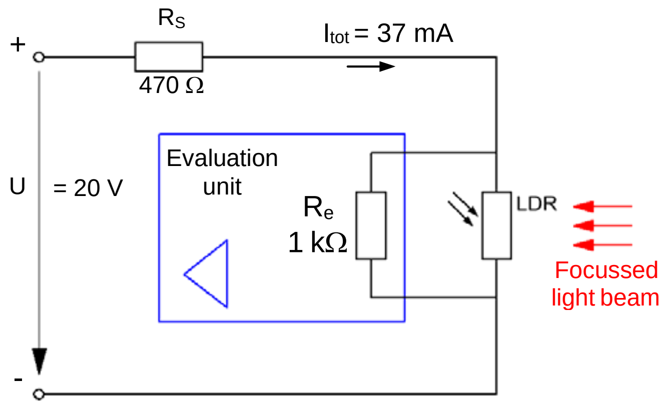


Fig. 3.3.5.1: Light barrier

- 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?

3.3.6 Exercise Assembly on the Electronic Circuits Board

Figs. 3.3.6.1 and 3.3.6.2 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.

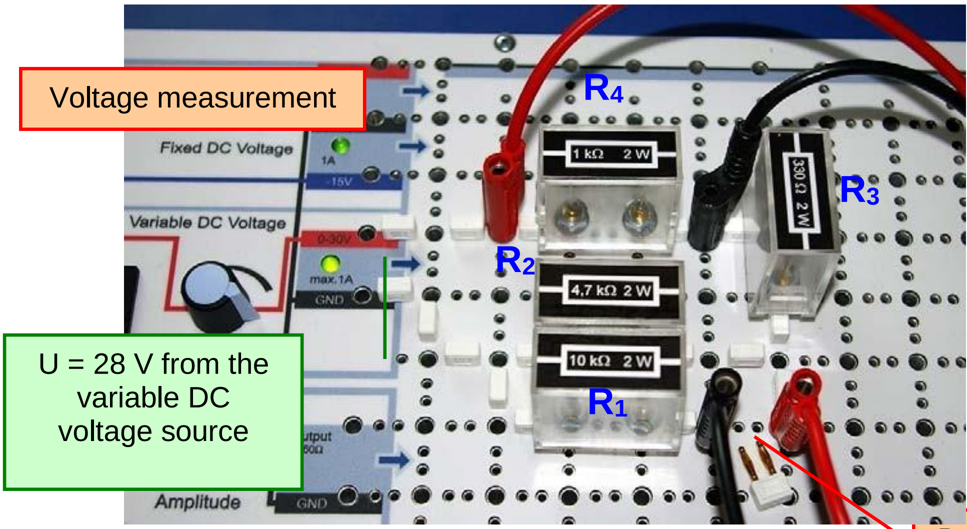


Fig. 3.3.6.1: Measurements on resistor network 1

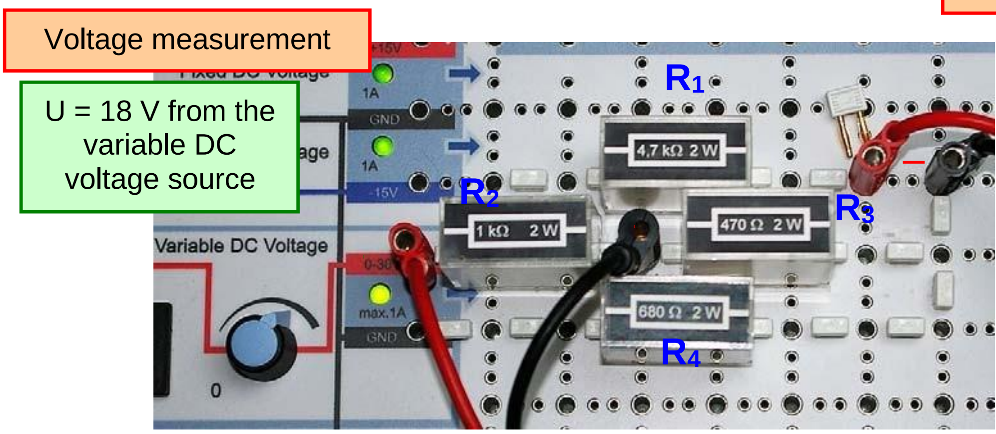


Fig. 3.3.6.2: Measurements on resistor network 2

Experiment (4)

4. Voltage Divider

4.1 The Off-load Voltage Divider

4.1.1 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. 4.1.1.1). Two connections form the input for the input voltage (U). At the output side, a partial voltage (U_2) is available across the resistor.

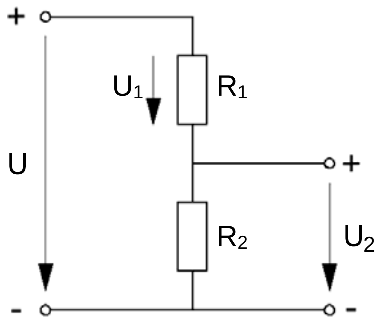


Fig. 4.1.1.1: Off-load voltage divider

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 sumof 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. 4.1.1.2). 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.

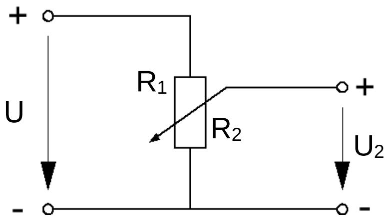


Fig. 4.1.1.2: Potentiometer

4.1.2 Practical Exercises with Off-load Voltage Dividers

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

- For the circuit in Fig. 4.1.2.1, calculate the output voltage U_2 and the voltage U_1.

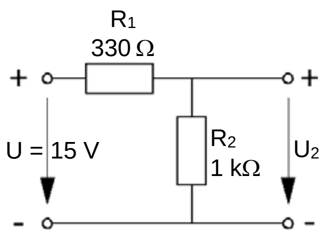


Fig. 4.1.2.1: Voltage divider

Assemble the circuit in Fig. 4.1.2.1on 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. 4.1.2.2 on the Electronic Circuits Board. Use an input voltage of U = 12 V (check the set value, on a multimeter).

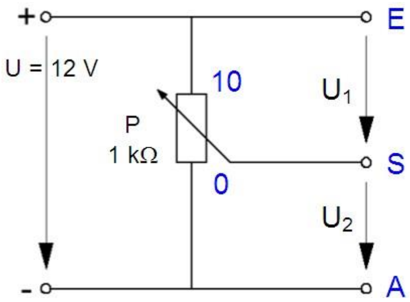


Fig. 4.1.2.2: Potentiometer

- Measure the output voltages U_1 and U_2 in relation to the slider setting (scale values). Enter the values measured in table 4.1.2.3.

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

Table 4.1.2.3: 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. 4.1.2.4) and draw the characteristics U_1 = f(scale value) and U_2 = f(scale value).

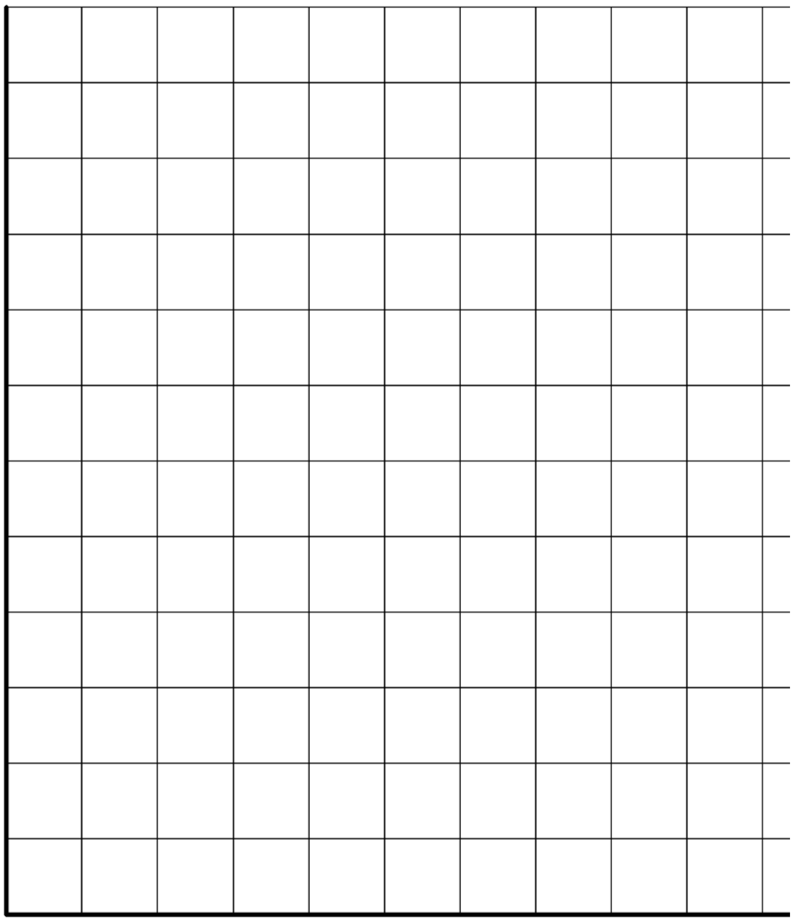


Fig. 4.1.2.4 Potentiometer characteristic

- 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'.

4.2 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. 4.2). The circuit here, has a load resistor R_L, that is in parallel to R_2 of the voltage divider (Fig. 4.2).

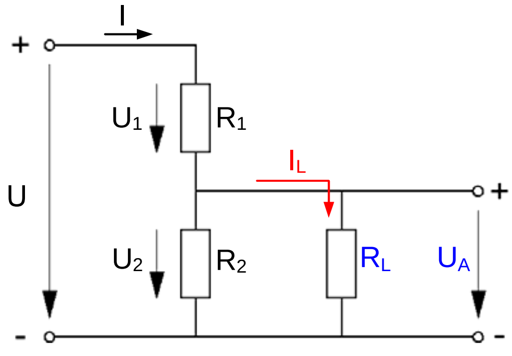


Fig. 4.2: Loaded voltage divider

4.2.1 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.

4.2.2 Practical Exercises with Loaded Voltage Dividers

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

The voltage divider shown in Fig. 4.2.2.1 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, mustnot 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.

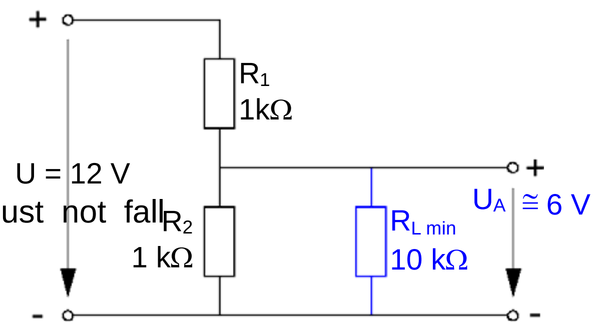


Fig. 4.2.2.1:

Exercise with a loaded voltage divider

- Assemble the circuit in Fig. 4.2.2.1 on the Electronic Circuits Board (Notes on assembly will be found in section 4.2.3). Apply a voltage of U = 12 V to the input ofthe 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 4.2.2.2: Measurements on a loaded voltage divider

U	$U_{A\text{ off-load}}$	$U_{A\text{ loaded (10 K}\Omega)}$	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. 4.2.2.1 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. 4.2.2.3 (check the set value, on a multimeter).

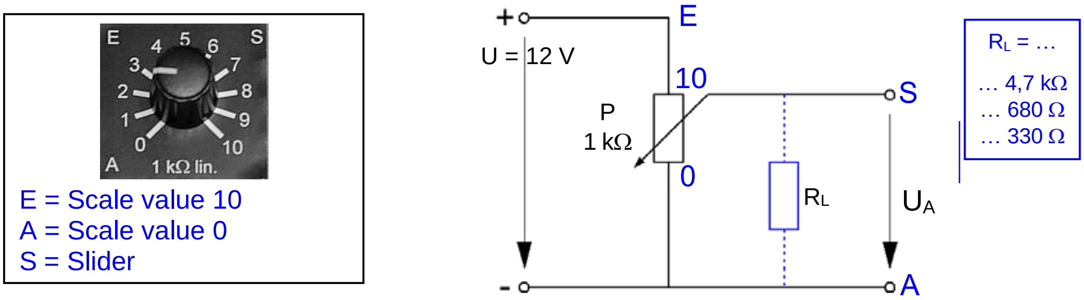


Fig. 4.2.2.3: Potentiometer with loaded output

- 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 outputvoltage U_A as a function of the slider setting (scale value). Enter the values measured into table 4.2.2.4.

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 4.2.2.4: Voltage measurements on a loaded potentiometer

- Plot the values from the table in the chart (Fig. 4.2.2.5) and draw the characteristics U_A = f(scale value).

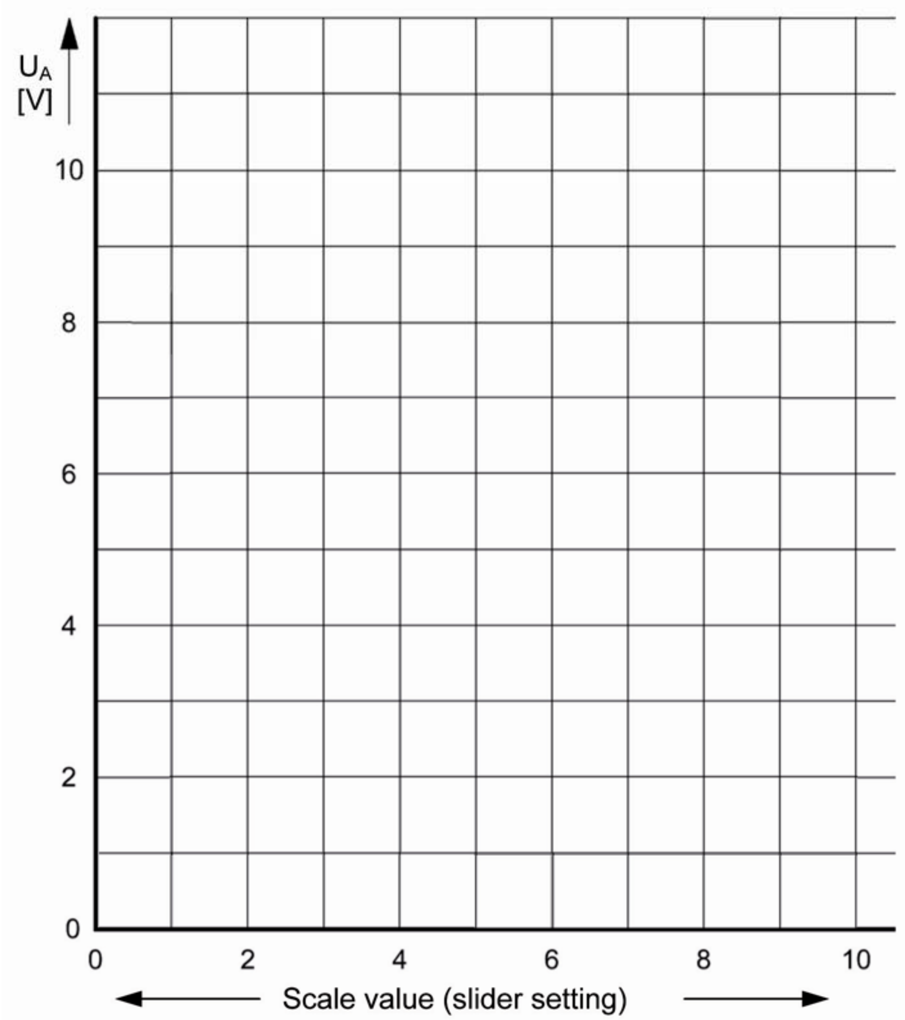


Fig. 4.2.2.5: Characteristics of the potentiometer with different loads

- 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 4.2.2.4. If the values differ, how do you explain the deviations?

4.2.3 Exercise Assembly on the Electronic Circuits Board

Loaded voltage divider with fixed resistance ratio

The layout shown in Fig. 4.2.3.1 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.

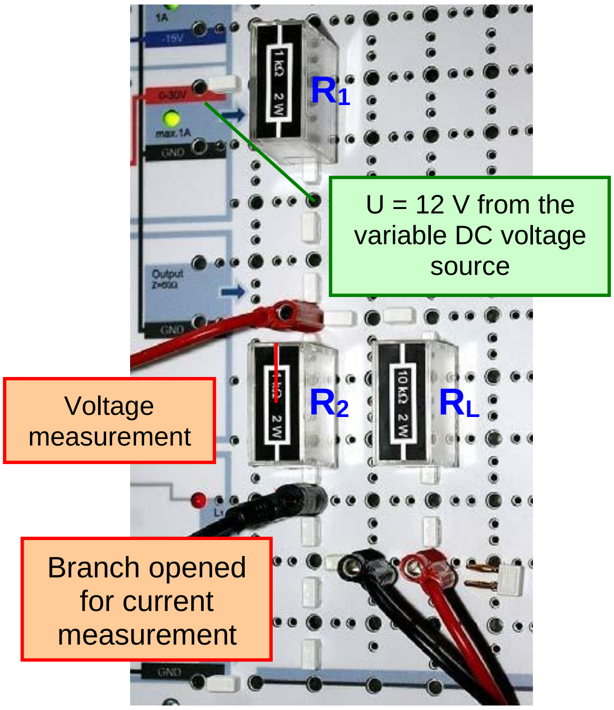


Fig. 4.2.3.1: Measurements on a loaded voltage divider with fixed resistance ratio

Loaded voltage divider with variable resistance ratio (potentiometer)

Fig. 4.2.3.2 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. 4.2.3.2, 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.

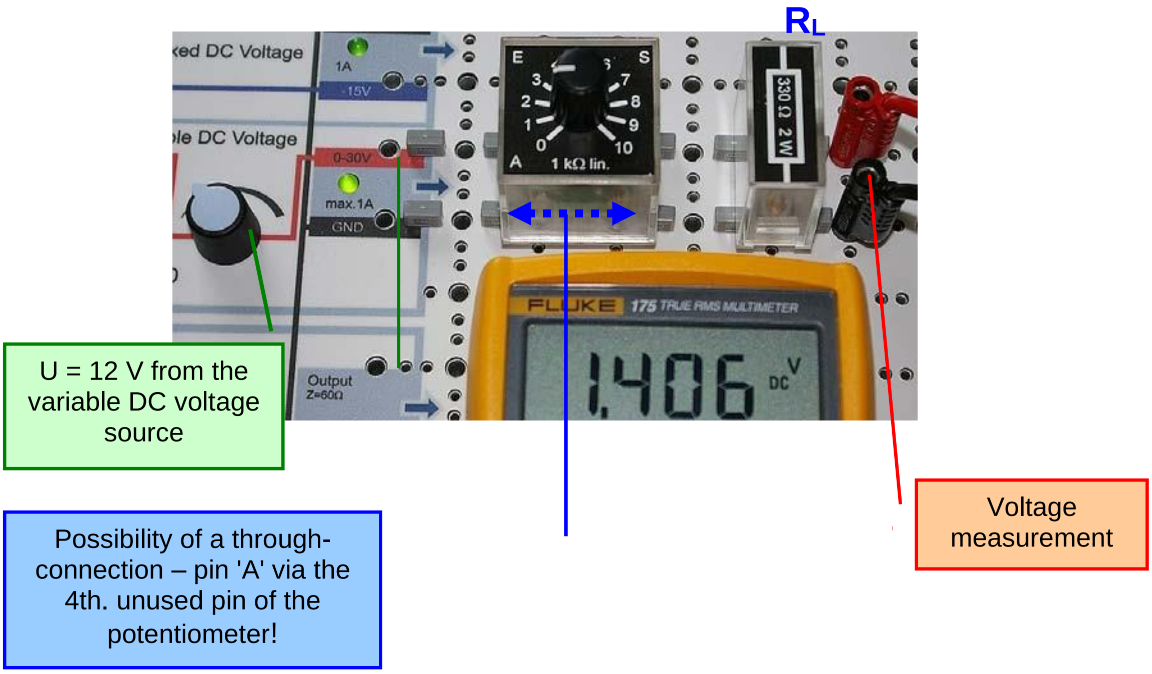


Fig. 4.2.3.2: Measurements on a loaded voltage divider with a potentiometer

Experiment (5)

5. Solution of network by means of Kirchhoff and superposition

5.1 Solution of the network by means of Kirchhoff

What are Kirchhoff's Laws? Kirchhoff's laws govern the conservation of charge and energy in electrical circuits.

Kirchhoff's Laws

1. The junction rule
2. The closed loop rule

Junction Rule "At any node (junction) in an electrical circuit, the sum of currents flowing into that node is equal to the sum of currents flowing out of that node, or: The algebraic sum of currents in a network of conductors meeting at a point is zero". The sum of currents entering the junction are thus equal to the sum of currents leaving. This implies that the current is conserved (no loss of current). $\sum Iin = \sum Iou$

Close Loop Rule: The principles of conservation of energy imply that the directed sum of the electrical potential differences (voltage) around any closed circuit is zero.

$\sum \Delta V_{close\ loop} = 0$

Procedure for Applying Rules

1. Assume all voltage sources and resistances are given. (If not label them V1, V2 ..., R1, R2 etc.)
2. Label each branch with a branch current. (I1, I2, I3 etc.)
3. Apply junction rule at each node.
4. Applying the loop rule for each of the independent loops of the circuit.
5. Solve the equations by substitutions/linear manipulation.

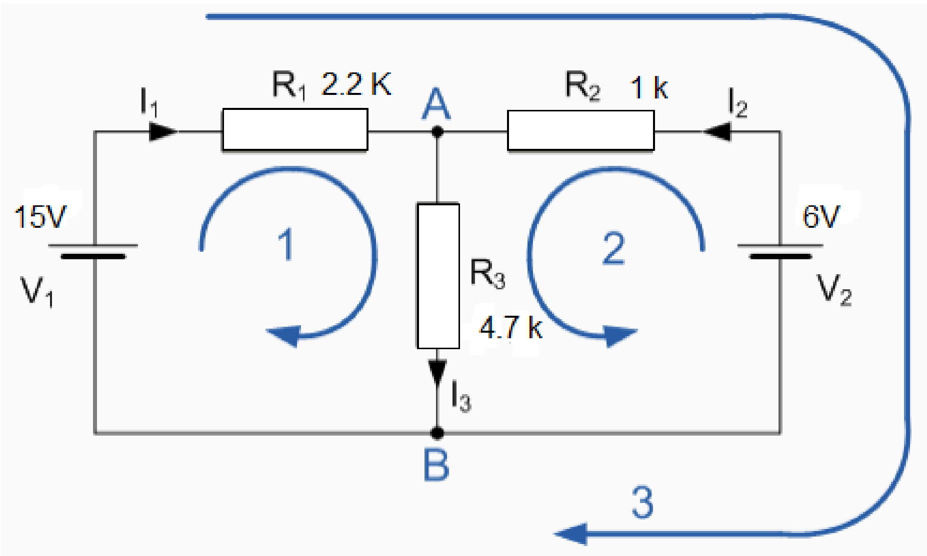


Fig. 5.1.1: Network analysis using KVL, and KCL.

The circuit in (Fig 5.1.1) contains two loops, with different current flowing in each. calculating this current will permit the further calculating of all the required quantities.

The circuit has two nodes (at A and B). We have the choice of choosing only two of the three loops shown (blue). This is because only two of the loops are independent.

Node A: $I1 + I2 = I3$

Node B: $I3 = I1 + I2$

Loop 1: $15 - I1R1 - I3R3 = 0$

Loop 2: $6 - I2R2 - I3R3 = 0$

A circuit analysis will be practiced on the example circuit in Fig 5.1.1

- Assemble the circuit of the Fig 5.1.1 on the electronic circuit board. Ensure that it will be possible to open the circuit at the locations required for current measurements.
- Set the voltage at the input of the circuit, to U_1 = 15 V, U_2 = 6 V (Check the value on the multimeter).
- Measure the voltage on each load U_{R1}, U_{R2}, and U_{R3} and enter the value in table 5.1.2.
- Measure the current on each load I_{R1}, I_{R2}, and I_{R3} and enter the value in table 5.1.2.
- Check the result using calculation using KCL, and KVL, and enter the value in the table 5.1.2

Resistor	Measured voltage (V)	Calculated voltage (V)	Measured Current (mA)	Calculated Current (mA)
R1				
R2				
R3				

Table. 5.1.2: Voltage measurement and current measurement.

5.2 Solution of the network by means of Superposition

The superposition principle states that the current in every resistor in network containing several voltage sources, is the sum of the currents resulting from each of the sources considered separately (regarding each of the sources as removed from the circuit and replaced by short circuit).

If we apply the superposition principle to the circuit in Fig 5.1.1, we obtain the two drawn in Fig 5.2.1, and Fig 5.2.2.

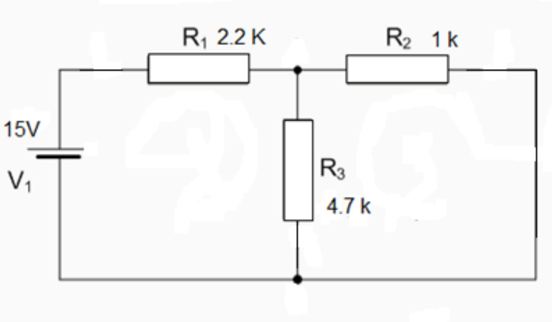


Fig. 5.2.1: Partial circuit with S.C on source 2.

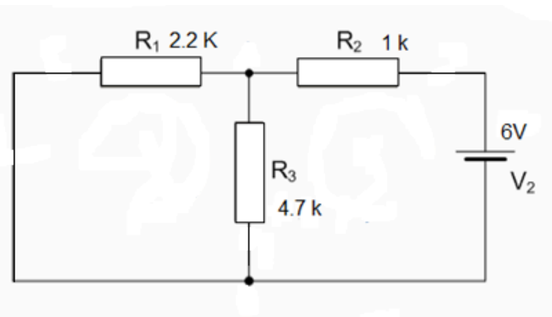


Fig. 5.2.2: Partial circuit with S.C on source 1

- First, assemble the circuit in Fig 5.2.1 keep source one, and replace the second source with short circuit.
- with a digital multimeter, measure the partial current and voltage for each load, enter the values in the table 5.2.3.
- Second, assemble the circuit in Fig 5.2.2 keep the second source, and replace the first source with short circuit.
- with a digital multimeter, measure the partial current and voltage for each load, enter the values in the table 5.2.3.
- Consider the direction of each current and voltage, calculate the total current and voltage on each load from partial values.

Measured						Calculated					
I_1’	I_2’	I_3’	V_1’	V_2’	V_3’	I_1’	I_2’	I_3’	V_1’	V_2’	V_3’
I_1’’	I_2’’	I_3’’	V_1’’	V_2’’	V_3’’	I_1’’	I_2’’	I_3’’	V_1’’	V_2’’	V_3’’
I_1	I_2	I_3	V_1	V_2	V_3	I_1	I_2	I_3	V_1	V_2	V_3

Table 5.2.3: Values measured with superposition principle.

Experiment (6)

6. Solution of network by means of Thevenin and Norton

6.1 Solution of network by means of Thevenin

Thevenin's theorem is an important tool in the solution of complex networks, it has an outstanding advantage over the methods discussed previously when it is desired to determine one current or one voltage drop in a network.

Let us deviate from our previous style, and instead of defining the theorem at the outset, we shall start with tan example. assume it is required to calculate the current flowing only through resistor R_3. let us call this the load resistor, and label its R_L. we disconnect it from the circuit we calculate or measure the voltage between terminals a and b let us call this voltage the equivalent voltage and label it E_{eq} Fig.6.1.1. nest we remove all voltage sources from the circuit and replace them with short circuit we look into terminal a and b and find the equitant resistor R_{eq} which exists between these terminals' Fig .6.1.2.

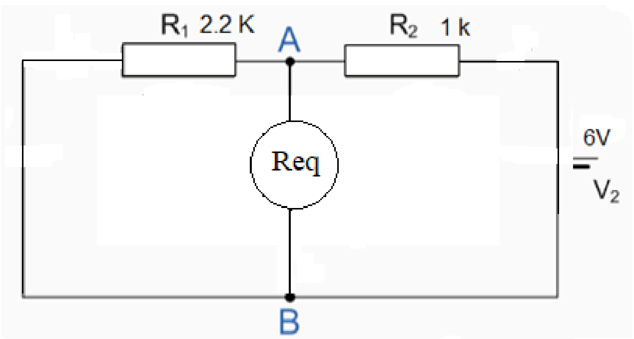


Fig. 6.1.1: Thevenin Equivalent voltage source.

Fig. 6.1.2: Thevenin equivalent resistance.

After finding the values of Eeq and Req, we can calculate the current through R_L in Thevenin equivalent circuit shown in Fig.6.1.3.

1- First, assemble the circuit in Fig 5.1.1 remove R_3, measure the voltage E_{eq} between node A and B in Fig 6.1.1 and write the result in the table 6.1.4.
2- Keep R_3 removed, replace the sources to short circuit and measure the equivalent resistance in Fig 6.1.2, write the result in the table 6.1.4.
3- Assemble Thevenin equivalent circuit in Fig 6.1.3 to measure the current and the voltage in the load resistance, write the result in the table 6.1.4.

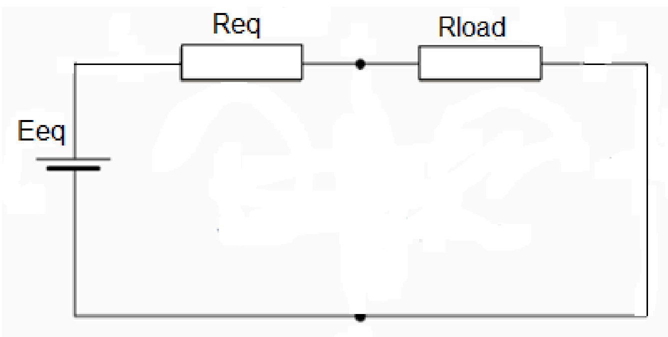


Fig. 6.1.3: Thevenin Equivalent circuit.

Measured				Calculated			
V_{Th}	R_{Th}	$I_{3(load)}$	$V_{3(load)}$	V_{Th}	R_{Th}	$I_{3(load)}$	$V_{3(load)}$

Table. 6.1.4: Thevenin Equivalent circuit result.

4- Check the result using calculation

6.2 Solution of network by means of Norton

The method of Norton is similar to the method of Thevenin the difference lies in the form of the equivalent circuit: in the method of Norton the equivalent source is a constant current source instead of a constant voltage source shown in Fig 6.2.1, as we used in the method of Thevenin.

The equivalent resistance in the method of Norton is identical in the value that calculated by the method of Thevenin shown in Fig 6.2.2, but here that resistance is connected in parallel to the equivalent source Fig 6.2.3 shows the equivalent circuit based on Norton theorem.

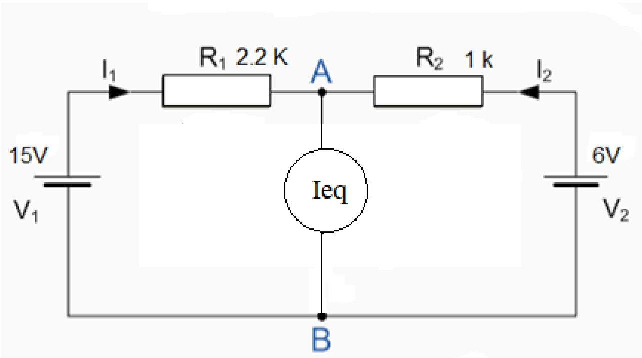


Fig. 6.2.1: Norton Equivalent current source.

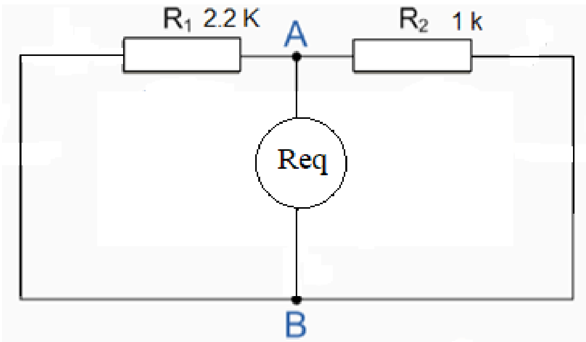


Fig. 6.2.2: Norton equivalent resistance.

After finding the values of I_{eq} and R_{eq}, we can calculate the current and the voltage through R_L in Norton equivalent circuit shown in Fig.6.1.3.

5- First, assemble the circuit in Fig 5.1.1 remove R_3, measure the current I_{eq} between node A and B in Fig 6.2.1 and write the result in the table 6.2.4.

6- Keep R_3 removed, replace the sources to short circuit and measure the equivalent resistance in Fig 6.2.2, write the result in the table 6.2.4.

7- Assemble Norton equivalent circuit in Fig 6.2.3 to measure the current and the voltage in the load resistance, write the result in the table 6.2.4.

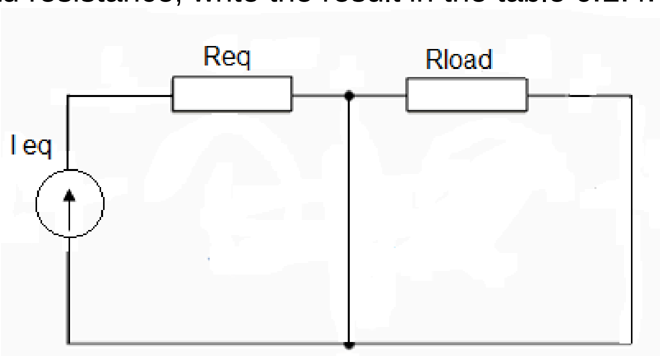


Fig. 6.2.3: Norton Equivalent circuit.

Measured				Calculated			
I_N	R_N	$I_{3(load)}$	$V_{3(load)}$	I_N	R_N	$I_{3(load)}$	$V_{3(load)}$

Table. 6.2.4: Norton Equivalent circuit result.

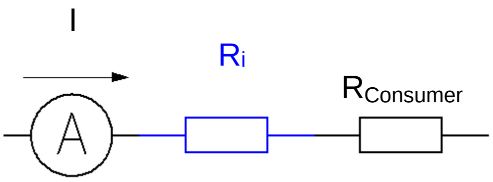
8- Check the result using calculation

Experiment (7)

7.1 Voltage and Current Error Circuits

7.1.1 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. 7.1.1, 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. 7.1.1, 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).



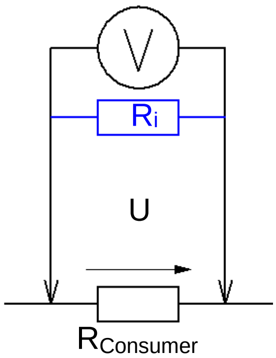


Fig. 7.1.1: Principles of current and voltage measurement

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. 7.1.1). 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.

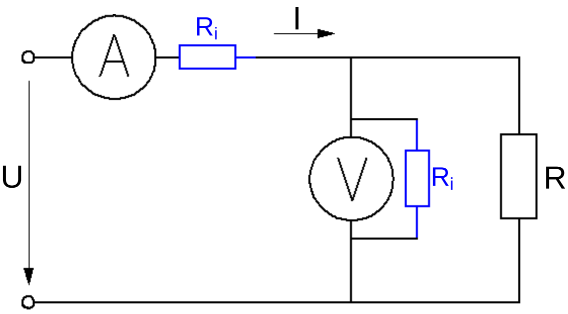
Therefore, careful considerations are essential **before** making any measurements, of the effect of test meters on the test object and the expected results of measurements.

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. 7.1.2 (current error circuit). At high-resistive consumers (kΩ and more), the connections shown in Fig. 7.1.3 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. 7.1.2: 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.

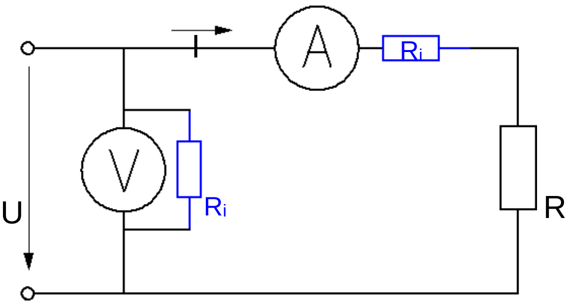


Fig. 7.1.3: Voltage error circuit

7.1.2 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 7.2.1 and 7.2.2. Note: If an accurate test meter is not available, enter the nominal values in the tables.
- Assemble the **current** error circuit in Fig. 7.1.2 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 7.2.1.

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

Table 7.2.1: Values measured with a current error circuit

- Assemble the **voltage** error circuit in Fig. 7.1.3 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 7.2.2.

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

Table 7.2.2: Values measured with a voltage error circuit

- Determine the difference ∆R between measured and calculated values of resistance. Enter the results in tables 7.2.1 and 7.2.2.
- 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?

7.2 Equivalent Voltage Sources

There are many types of voltage source electrochemical (batteries) electrical (generators) and electronics (rectifier, regulated power supplies, etc..) all of them can be represented by an equivalent circuit such as appears in Fig .7.2.1.

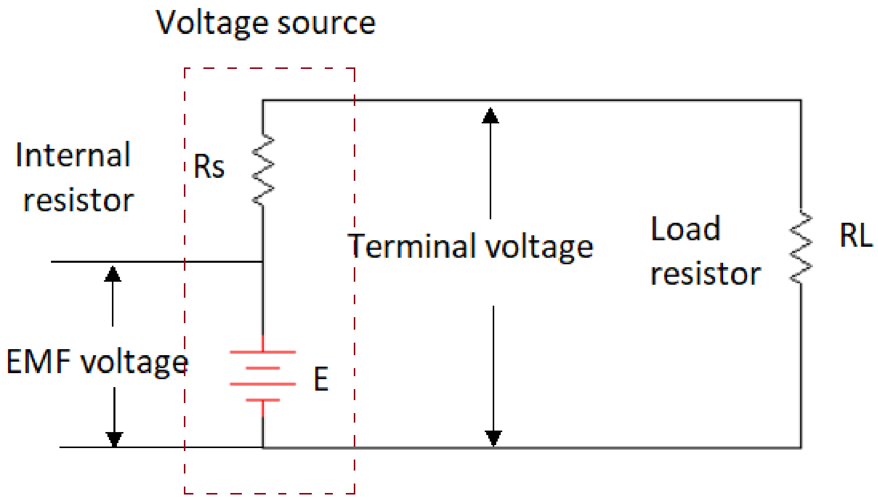


Fig. 7.2.1: equivalent circuit of voltage source.

Three electrical quantities characterized the voltage source: its electromotive (EMF) labelled E; its internal resistance, labeled Rs; and its terminal voltage labeled V. the first two quantities depend on the construction of the source; they cannot be separated from each other, and there is no physical access to them. their values can be identified only by means of measurements as will be shown below the terminal voltage of the source is the voltage that appears across its output terminals. this quantity as opposed to the first two, is not dependent solely on the characteristic of the source itself, but also on the external circuit connected to the source; or more precisely, on the current drain from the source.it is easy to show from the description of the equivalent circuit that the terminal voltage will be lower than the EMF so long as current flows in the circuit.

To find the value of the EMF, the terminal voltage must be measured when the source current equals zero. for this reason, the EMF must be measured by means of a voltmeter with very high internal resistance compared to the internal resistance of the voltage source.

The internal resistance of the voltage source can be identified by the source with variable load resistance. the terminals voltage is measured while varying the load. that the load which causes the terminal voltage is to half the EMF is equal to the internal source resistance (which is desired to determine)

The presence of internal resistance in the voltage source the terminal voltage to vary when the current drain varies. this statement is expressed mathematically by equation: expressed graphically and in Fig .7.2.2

$$V = E - I * R_S$$

Where v is the terminal voltage, in volts

E: is the EMF, in volts

I: is the current supplied by the source in amperes.

Rs: is the internal resistance of the source in ohms.

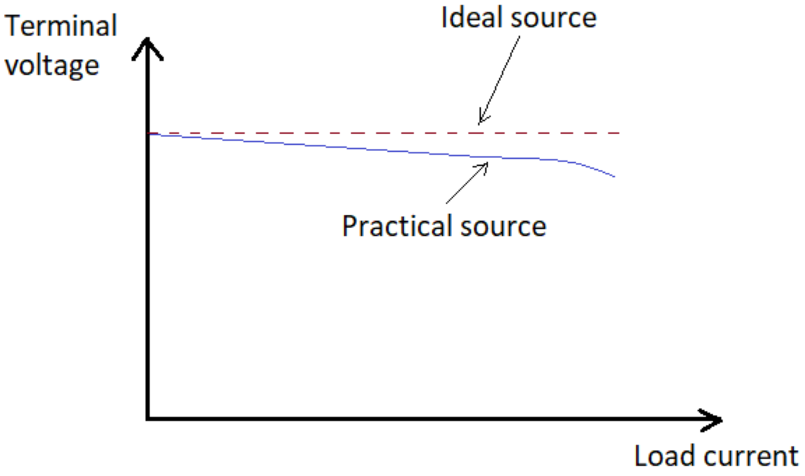


Fig. 7.2.2: terminal voltage as a function of load current.

The following conclusion derive from Fig 7.2.2:

A- An ideal voltage source is one in which the terminal voltage is constant, and independent of current drain. for this condition to exist, the internal resistance of the source must equal zero in such a case the terminal voltage would be constant, and equal in value to the source EMF.

B- The terminal voltage of a practical voltage source depends on the current drain (because of the voltage drop across the internal resistance) and decreases with increasing current drain.

In the real world, there are no voltage source with zero internal resistance in the voltage source is a primary battery) when it is new internal resistance is low. But as the battery ages or its capacity is drained the internal resistance increases. the same rule holds for a rechargeable battery. it is worth mentioning that for both these sources, it is the internal resistance which change with time, and not the EMF. the latter remains constant, because its value depends on the construction of the source only, and not on its age or the rate of current drain from it.

Voltage source such as generator or electronic power supplies excel in having fixed in having a fixed internal resistance, which is generally very low. the higher the quality of the source, the lower is its internal resistance. in modern electronic source, the internal resistance reaches the order of thousandths of an ohm.

7.2.1 Constant voltage source and constant current source

One must distinguish between an ideal voltage source and a constant -voltage source. The ideal voltage source maintains a constant terminal voltage for every current drain dictated by the external circuit. as was noted above, the condition for attaining an ideal voltage source is that the internal resistance is equal to zero. A constant -voltage source, on the other hand, has a constant terminal voltage for certain circuit conditions, which are described below.

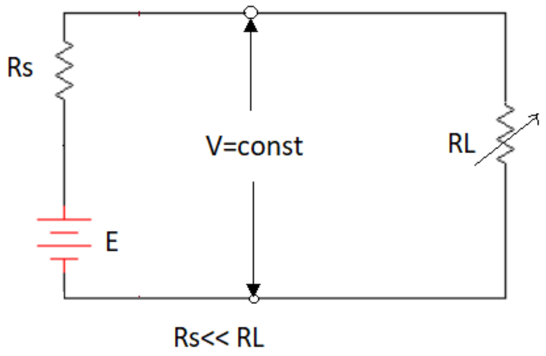


Fig. 7.2.1.1: constant voltage source.

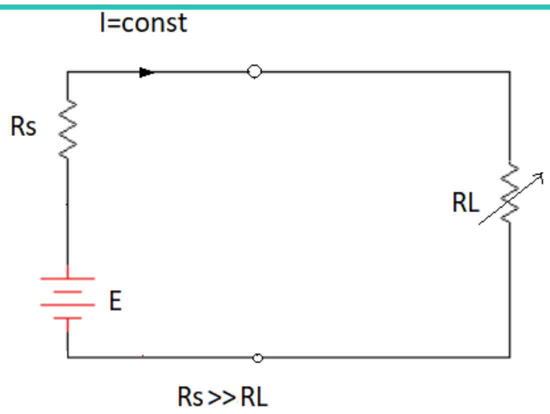


Fig. 7.2.1.2: constant current source.

Let as examine Fig. 7.2.1.1, which shows the circuit of the voltage source. assume that in this circuit, E=10v, R_S=0.1Ω, R_L=10KΩ

The terminal voltage V, in this case, will be:

$$V = E - I * Rs = 10 - \frac{10}{0.1 + 10000} * 0.1 = 10v$$

Now let us change the load resistance to RLΩ=9K. the new terminal voltage V, will be:

$$V = E - I * Rs = 10 - \frac{10}{0.1 + 9000} * 0.1 = 10v$$

It is clear from the above example that the terminal voltage remains (nearly constant, despite the fact that the load resistance was changed by 10%. This is because the internal resistance, Rs, had a very low value, which was negligible in comparison to the load resistance.

Thus, a voltage source will be called "constant if its internal resistance is very low compared to the load resistance, over the entire range of load variation.

In a similar manner, we can define a constant-current source, thus is a source (voltage, in fact) with internal resistance very high compared to the load resistance. thereby, in every case where this relationship is maintained, the current will be determined by the internal resistance of the source. Thus, in the circuit of this type, changing the load causes (nearly)no change in current; therefore, the source supplies, in fact, a constant current Fig 7.2.1.2.

7.2.2 Maximum power transfer

In very many cases, maximum power transfer from the source to the load is required. Assume a source with given values of EMF and internal resistance let us vary the load resistance and check on the change of current, voltage and power developed in the load. it is very easy to show that the lower the load resistance, the greater will be the current flow through the load, while the smaller will be the voltage drop developed. on the other hand, it is difficult to analyze logically the power transferred to the load as a function of the load resistance.

We can prove mathematically that the maximum power is transferred to the load when the load resistance equals the internal source resistance. in every case where the load and source resistance differ, the power transferred to the load is less than the maximum power. Fig 7.2.2.1 this is phenomenon graphically.

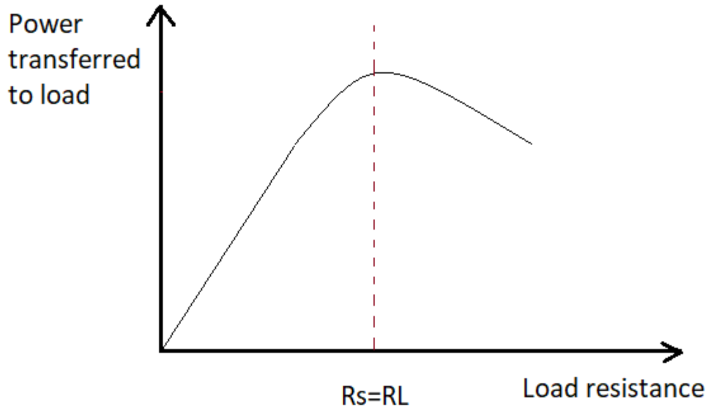


Fig. 7.2.2.1: power transferred to load as a function of load resistance.

The power transferred to the load is connected with the concept of "efficiency". the efficiency (η) is the ratio between the power developed in the load, and the power supplied by the source:

$$η(\%) = \frac{Pl}{Ps} * 100$$

Where η: is the efficiency, in percent.

PL: is the power developed in the load, in watts.

PS: is the power supplied by the source, in watts.

Additional mathematical development of the efficiency equation will prove that the efficiency is always less than 100%. this is due to the power dissipated in the internal load resistance:

$$η(\%) = \frac{Pl}{Ps} = \frac{I^2 * RL}{I^2 * RT} = \frac{RL}{RT} = \frac{RL}{RL + Rs}$$

It is interesting to note that the efficiency in the case of maximum power transfer is not the maximum imaginable, but only equal to 50%. to prove this, we substitute the relation R_L=R_S into equation and obtain:

$$η(\%) = \frac{RL}{RL + Rs} = \frac{RL}{2RL} = 0.5$$

Procedure of this experiment:

Voltage source component EMF and terminal voltage

1- Connect the circuit as shown in the Fig 7.2.4 assembling it on board.

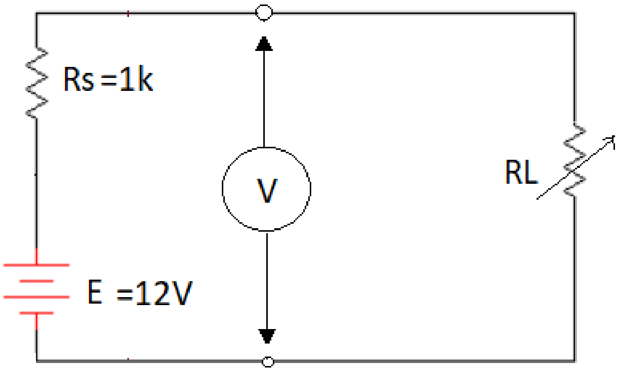


Fig. 7.2.3: identification of voltage source components.

2- R_p represent the source resistance, and is set on board.
3- Connect the resistor to the terminals on board this is labelled R_L here.
4- Measure the terminals voltage with the resistor R_L disconnected.

Record the result in table 7.2.1:

Internal resistance (Ω)	**Terminal voltage** (V)

Table 7.2.1: identification of voltage source components.

The voltage sources

In the circuit shown in Fig 7.2.3 vary the resistance as specified in table each time measure the output voltage record the result in table 7.2.2

Load resistance (Ω)	**Output voltage** (V)	**Load current** (mA)
330		
470		
680		
1000		
2200		

Table 7.2.2: load voltage and current as a function of load resistance.

The source as a constant -voltage source

In the circuit shown in Fig 7.2.3 vary the resistance as specified in table 7.2.3 each time measure the load voltage

Record the result in table 7.2.3

Load resistance (KΩ)	**Measured output voltage** (V)	**Calculated output voltage** (V)
10		
22		
47		
68		
100		

Table 7.2.3: the source as a constant voltage source.

The source as a constant -current source

Connect the circuit as shown in Fig 7.2.3 assembling it on board, Rp represent the internal resistance connect the resistor RL

Vary the value of the resistance as specified in table 7.2.4, each time measure the current. record the result in table 7.2.4.

Load resistance (Ω)	**Measured load current (mA)**	**Calculated load current(mA)**
10		
22		
33		
100		
220		

Table 7.2.4: the source as a constant current source.

Maximum power transfer and efficiency

Connect the circuit shown in Fig 7.2.3.

Vary the value of the resistance as specified in table7.2.5, each time measure the load voltage. record the result in table 7.2.5.

Load resistor (KΩ)	**TERMINAL VOLTAGE (V)**	**LOAD POWER (mW)**	**EFFICIENCY (%)**
0.1			
0.15			
0.22			
0.33			
0.47			
0.68			
1.0			
1.5			
2.2			
3.3			
4.7			
6.8			
10			

Table 7.2.5: maximum power transfer and efficiency.

Experiment (8)

8. Types of Current (Voltage) and their Characteristics

8.1 Types of Current (Voltage)

The discussions up to now, have dealt exclusively with electrical processes based on the flow of a **direct current** (DC) A property of DC is the **constancy with respect to time of the magnitude of the current**. This causes a **continual flow of current inone direction** in an electrical circuit. The magnitude and direction of the DC current is caused by a constant **DC voltage**. At various instants of time (t_1, t_2, etc.), stableconditions can be measured at the terminals of a DC voltage source, in the circuit andat the consumer[1]. Fig. 8.1.1 shows the voltage and flow of current over a period of several seconds.

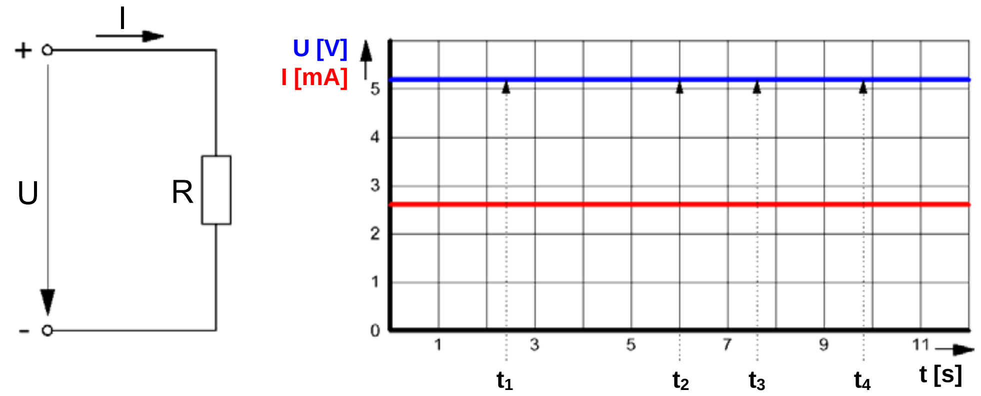


Fig. 8.1.1: Time characteristic of DC voltage and current

The term **alternating current** is used when the current in a circuit periodically changes in magnitude and direction. This alternating current (AC) is caused by an alternating voltage applied to the circuit.

Fig. 8.1.2: Examples of alternating voltages

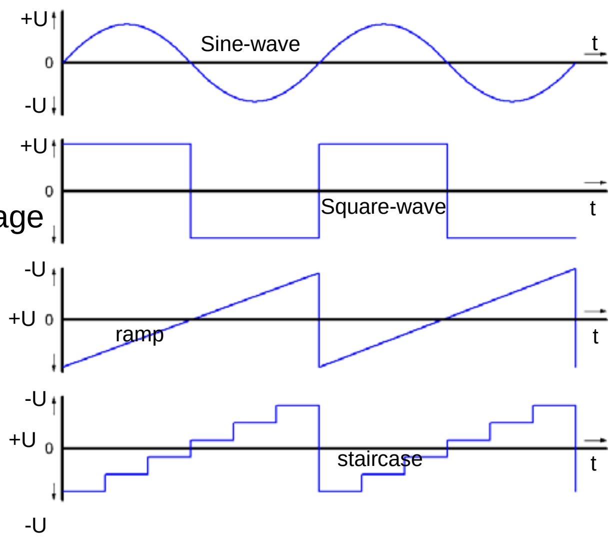
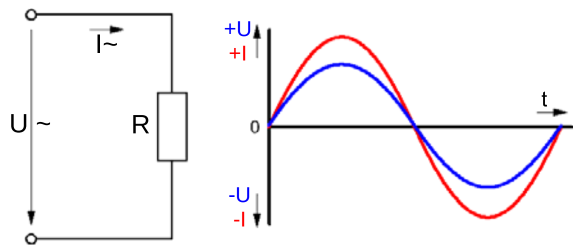


Fig. 8.1.2 shows various forms of AC voltage that have been displayed on an oscilloscope, used in circuits depending on the required effect or function of the circuit. The voltage curves shown are known as '**sine-wave**' (or sinusoidal), '**square-wave**', '**ramp**' (or sawtooth) and '**staircase**' voltages. For all voltages above the zero axis (+U) a varying current flows according to the magnitude (or '**amplitude**') of the voltage, in the same direction. When the voltage changes to the area below the zero axis (-U), the current flows in the opposite direction.

8.2 Characteristics of Sine-wave Voltages (and Current)

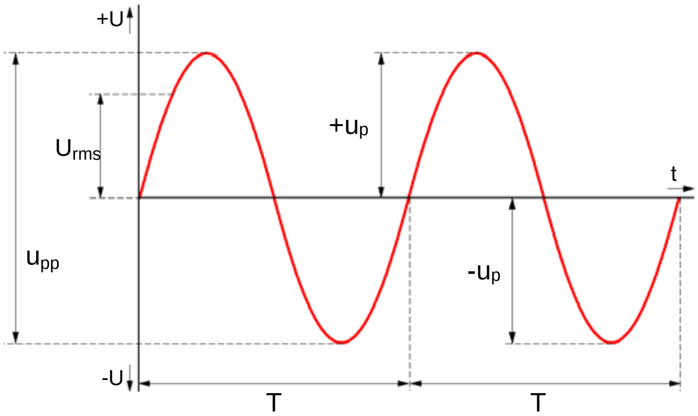
8.2.1 Derivation of the Characteristics



At pure ohmic consumers, such as a simple resistor, the responses of voltage and current follow the same conditionswith respect to time (Fig. 8.2.1.1). Voltage and current are said to be '**in phase**'. The descriptions of the characteristics that follow assume corresponding temporal conditions forvoltage and current.

Fig. 8.2.1.1: Voltage and current, 'in phase'

Fig. 8.2.1.2: Characteristics of a sine-wave voltage



The amplitude between the zero axis and maximum value, is known as the **peak value (u_p)** of the sine-wave (Fig. 8.2.1.2) and can a be positive ($+u_p$) or negative ($-u_p$) value. The voltage between the peak values (Fig. 8.2.1.2) is known as the **peak-to-peak value (u_{pp})**. These properties of the voltage can be displayed and measured on an oscilloscope. If an alternating voltage (or current), is measured with a voltmeter (or ammeter), the indicated value corresponds to the effective value of voltage (or current). This effective value is more often referred to as the **root mean square value** (U_{rms} or I_{rms}). The following relationships between rms values and peak values for sine-wave voltages or currents:

$$U_{rms} = \frac{1}{\sqrt{2}} \cdot u_p \quad \cong \quad 0{,}707 \cdot u_p \qquad ; \qquad I_{rms} = \frac{1}{\sqrt{2}} \cdot i_p \quad \cong \quad 0{,}707 \cdot i_p$$

From the sine-waves shown in Figs. 7.2.1.1 and 7.2.1.2, the regular recurrence of maxima, minima and crossing of the zero axis, exhibit a *periodic response*. This 'period of oscillation', or **periodic time, T** specifies the length of time after which the voltage or current wave is repeated. Using this periodic time T, the **frequency, f** of an alternating voltage can be determined. Thus:

$$f = \frac{1}{T} \qquad \left[1Hz = \frac{1}{1s} = 1s^{-1}\right]$$

1 Kilohertz	=	1 kHz	=	1.000 periods/s
1 Megahertz	=	1 MHz	=	10^6 periods/s
1 Gigahertz	=	1 GHz	=	10^9 periods/s

The unit of frequency is the Hertz (named after the German physicist *Heinrich Rudolf Hertz* in 1935). Commonly used units are also kilo-, Mega- or Gigahertz.

The same characteristic quantities (i.e. U_{rms}, u_p, T, f) are used in part, for other waveforms of voltage (square-wave, ramp, etc.). It must be remembered here, that the relationship between the effective voltage U_{rms}, and the peak voltage u_p depends on the shape of the voltage waveform.
For various other calculations, especially on non-ohmic components, the **angular frequency** ω is used, given by the periodic time T or frequency, f[2]:

$$\omega = 2 \cdot \pi \cdot \frac{1}{T} \quad \Rightarrow \quad \omega = 2 \cdot \pi \cdot f \qquad \left[1\,\frac{\text{rad}}{s}\right]$$

Occasionally in calculations, the **instantaneous value u** or **i** of a sine-wave is required. Here, the following equations are used:

$$u = u_p \cdot \sin \omega \cdot t \qquad ; \qquad i = i_p \cdot \sin \omega \cdot t$$

Current requires time to flow from one pole through a circuit, to the other pole. Assuming a sufficiently long cable, there are several minima, maxima and zero passes of an alternating current present along a connection cable, simultaneously. The longer the cable (or, the higher the frequency), the more complete periodic time intervals are formed along the cable at the same time. The distance bridged by one periodic time T is known as the **wavelength,** λ. The name stems from the wave shape of a sine-wave oscillation. The wavelength λ is given by the quotient of the velocity of propagation of a wave v and the frequency f:

$$\lambda = \frac{v}{f} \qquad ; \qquad \lambda_{space} = \frac{c}{f}$$

Under certain conditions, electrical energy can also radiate (or propagate) in free space in the form of waves, without any conducting connection (e.g. radio waves, mobile telephone, etc.) In this case, the velocity of propagation is the same as the speed of light, c (~ 300.000 km/s)[3]. In conducting materials, the velocity of propagation of electrical waves is approximately 30% less than the speed of light in free space.

8.2.2 Characteristic Quantities of a Sine-wave Voltage in a Practical Exercise

The characteristic quantities are to be measured and their inter-relationships proved, in a circuit consisting of an AC voltage source (generator G ~) and a load resistor R_L,.

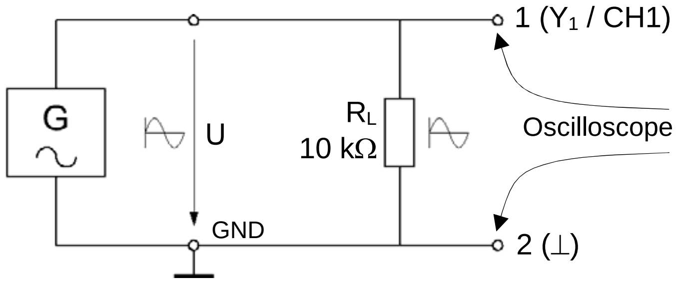


Fig. 8.2.2.1: Sine-wave generator with load resistor, R_L

- Assemble the circuit in Fig. 8.2.2.1 on the Electronic Circuits Board (notes on assembly will be found in section 8.2.3).

[2] The unit 'rad' (radian) indicates that the value is the magnitude of an angle (in circular measurements)
[3] Strictly speaking, the propagation velocity of waves of electrical energy is equal to the speed of light, only in a vacuum.

- Connect channel 1 (Y_1 or CH1) of your oscilloscope – as in Fig. 8.2.2.1 – to test terminals (outputs) 1 and 2 of the circuit.
- Set the output of the function generator on the Electronic Circuits Board, between the sockets 'Output' and 'GND', to the sine-wave voltage shown in Fig. 8.2.2.2. With the given values of timebase and amplitude, the sine-wave should be displayed on the oscilloscope as shown in Fig. 8.2.2.2.

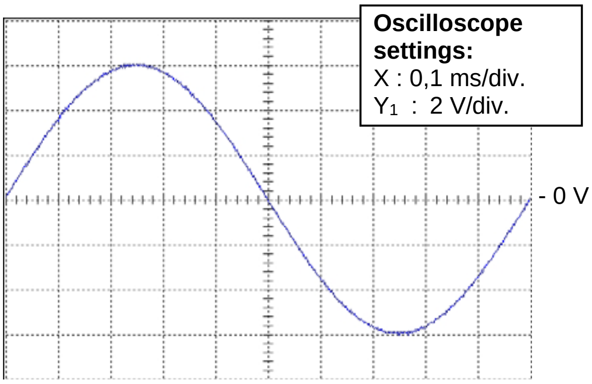


Fig. 8.2.2.2: Sine-wave voltage on the oscilloscope

- Measure the values required to complete table 8.2.2.1, from the oscilloscope display. Measure the instantaneous value of voltage u, 0,6 ms after the start of a period.

Table 8.2.2.1: Measurements on the oscilloscope

$+u_p$	$-u_p$	u_{pp}	u (after 0,6 ms)	T

- Calculate the following quantities from the values in the table: **i_S, U_{rms}, I_{rms}, f, ω, λ.**

- Check the instantaneous value of voltage, u, read from the oscilloscope, by calculation.

Check the calculated value of effective voltage, U_{rms} with the multimeter.

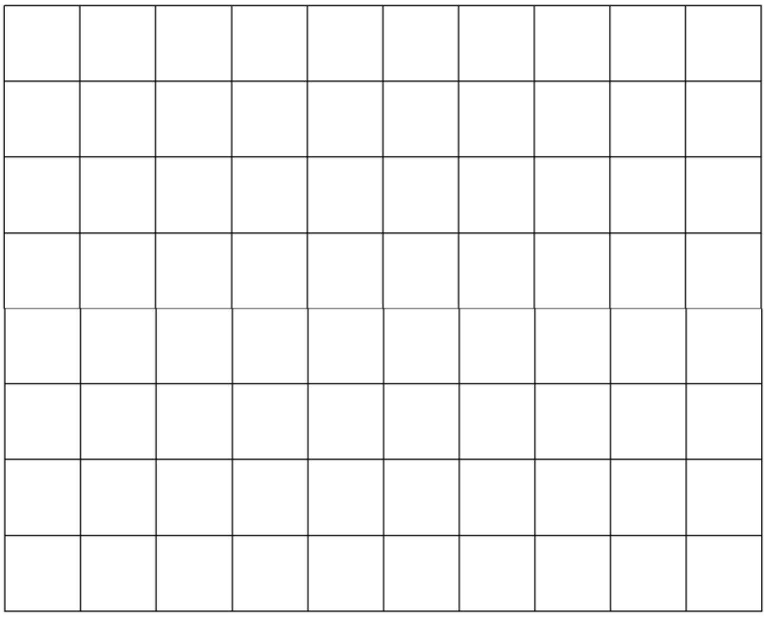
U_{rms} =

- At the output of the function generator, a sine-wave voltage of U_{rms} = 8 V at a frequency, f = 250 Hz should be present. First, calculate u_p, u_{pp} and T.

- Adjust the frequency of the function generator to f = 250 Hz. Use the meter on the function generator when adjusting the frequency. Adjust the effective voltage, U_{rms} = 8 V, whilst measuring with the multimeter at the same time.
- First, check the calculated characteristic quantities of the output AC voltage on the oscilloscope. Draw the sine-wave in the chart below (Fig. 8.2.2.4).

Fig. 8.2.2.4:
Oscilloscope display,250 Hz sine-wave, 8 V rms

Oscilloscope settings:
X : 1 ms/ div.
Y_1 : 5 V/ div.



- What time elapses after the start of a period, before the sine-wave signal reaches a voltage of 5 V? Calculate the value and check the result on the oscilloscope.

8.2.3 Exercise Assembly on the Electronic Circuits Board

The Function Generator on the Electronic Circuits Board is used for the exercises. It incorporates 4 possibilities of adjustment (Fig. 8.2.3.1):

a. The 'Waveform' of the alternating voltage can be selected by the push-button switch 'Press to change'.

b. The frequency is adjusted by way of the control marked 'Frequency' (range, 0 Hz to 210 kHz, stages depending on range).

c. By pressing the control knob 'Frequency', the frequency is immediately latched at 1 kHz ('Fixed 1 kHz').

d. The amplitude of the output voltage can be varied over the range 0 to ~ 7 V_{rms} with the 'Amplitude' control.

Fig. 8.2.3.1 shows the connections for the oscilloscope or multimeter for measuring the output AC voltage of 1 kHz.

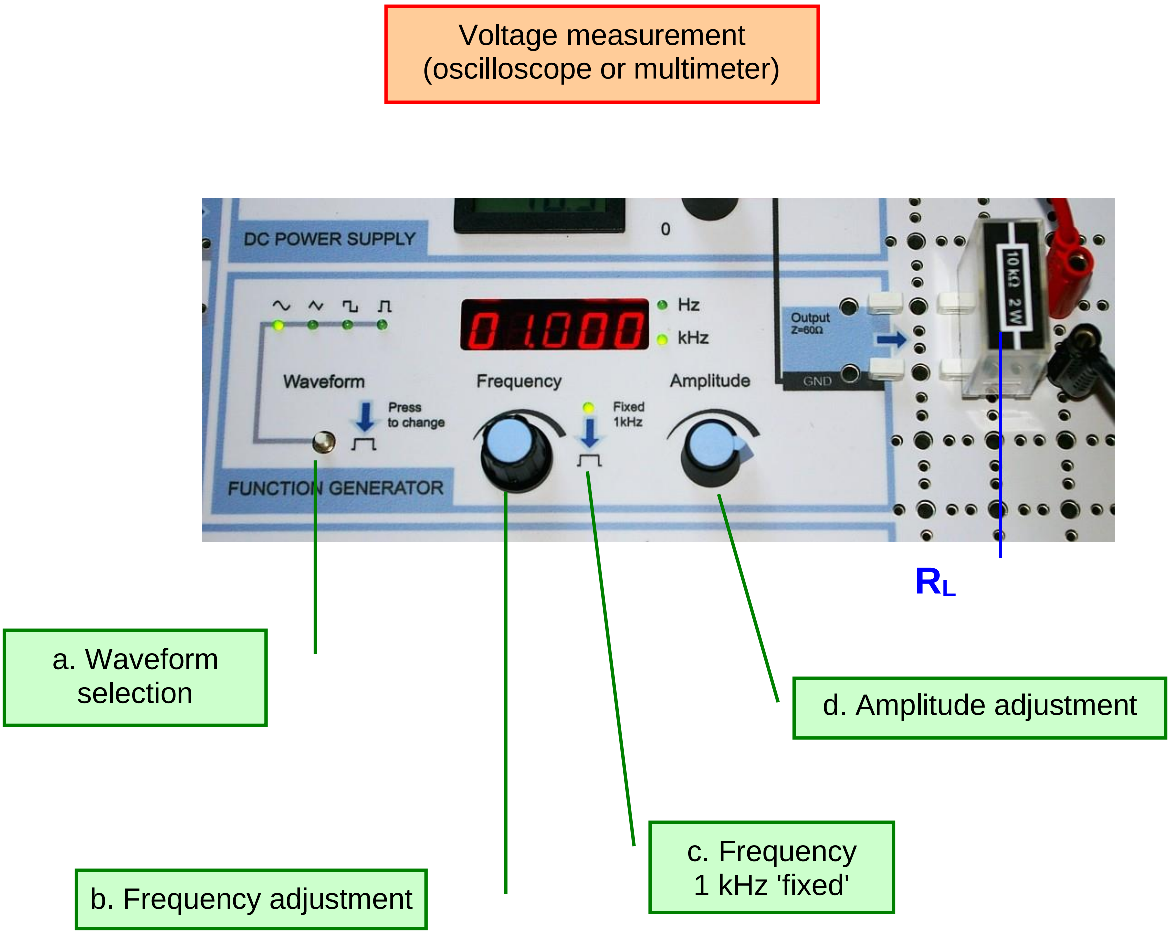


Fig. 8.2.3.1: Adjustment facilities on the function generator on the Electronic Circuits Board

8.3 Characteristics of Square-wave Voltages

8.3.1 Derivation of the Characteristics

As with sine-wave voltages, the **periodic time, T** specifies the length of time after which the voltage wave is repeated (Fig. 8.3.1.1). Thus, the same expressions applies for the frequency:

$$f = \frac{1}{T} \qquad \left[1Hz = \frac{1}{1s} = 1s^{-1} \right]$$

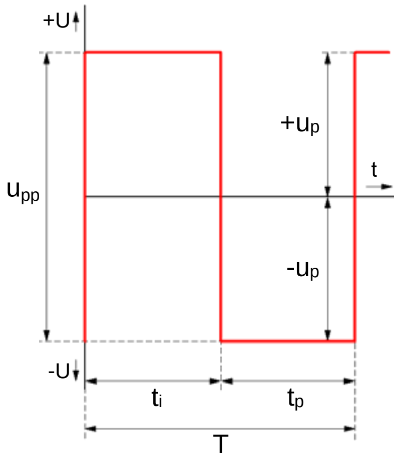


Fig. 8.3.1.1: Characteristics of a square-wave voltage

Of more interest with square-wave voltages, are the sections of the wave-form known as **pulse duration t_i** and **interpulse period t_p**. The 'pulse duration' is the time taken for the voltage to rise in a positive direction until the fall in a negative direction (Fig. 8.3.1.1). The 'interpulse period' is similarly defined in the opposite direction. The pulse duration t_i and interpulse period t_p are added to give the periodic time, T. The ratio of t_i to T is known as the **duty factor, g**. Quite often the term **duty cycle** is used although this applies more to a train of square-wave pulses:

$$T = t_i + t_p \qquad ; \qquad g = \frac{t_i}{T}$$

If the pulse duration t_i and interpulse period t_p are the same length, the duty factor g is then 0,5. Also, if the duration of both peak values are of the same magnitude ($+/-u_p$) then reference is made to a '**symmetrical square-wave voltage**' (Fig. 8.3.1.1).

Peak values ($+/-u_p$) and **peak-to-peak values (u_{pp})** are given as with a sine-wave voltage, between maximum, minimum and zero axis (c.f. Figs. 8.2.1.2 and 8.3.1.1).

With s*ymmetrical* square-wave voltages the effective value, U_{rms} corresponds to the peak value u_p. This is easier to understand if one imagines the negative section to be folded up to the positive side of the zero axis.

The same statement applies to the current flows (i_{pp}, i_p, I_{rms}) caused by square-wave voltages.

8.3.2 Characteristic Quantities of a Square-wave Voltage in a Practical Exercise

The characteristic quantities will now be derived from measurements on a symmetrical square-wave voltage circuit as shown in Fig. 8.3.2.1.

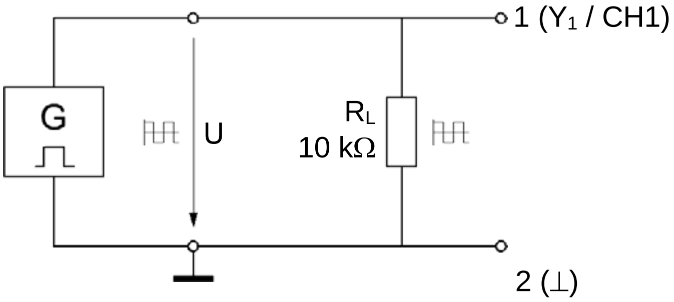


Fig. 8.3.2.1: Circuit with square-wave generator

- Assemble the circuit in Fig. 8.3.2.1 using the function generator, on the Electronic Circuits Board.
- Connect channel 1 (Y_1 or CH1) of your oscilloscope to outputs 1 and 2 of the circuit.

- Set the output of the function generator to a symmetrical square-wave voltage with the following values: f = 625 Hz, U_{rms} = 6 V. To check the settings, use the frequency meter on the Board and a voltmeter.

- Display the square-wave voltage on the oscilloscope and draw the waveform in the chart given in Fig. 8.3.2.2.

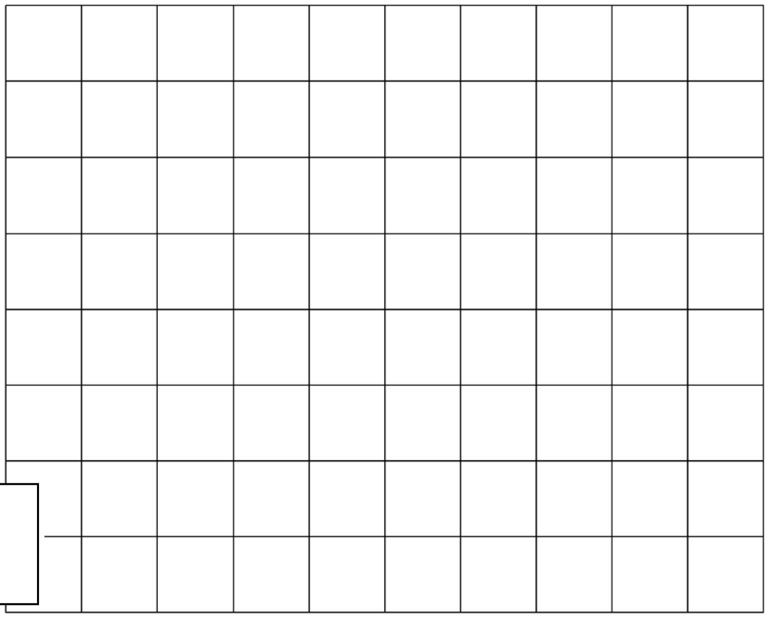


Fig. 8.3.2.2: Square-wave voltage on the oscilloscope

- Measure the values of u_{pp}, u_p, T, t_i and t_p from the oscilloscope display.

Oscilloscope settings:
X : 0,4 ms/ div.
Y_1 : 2 V/ div.

u_{pp} = ; $|+u_p|$ = $|-u_p|$ =

T = ; t_i = ; t_p =

- Calculate the peak current i_p and the duty factor of the square-wave voltage.

- Check the set frequency by calculation.

- What is the relationship between the peak value u_p read on the oscilloscope, and the value of effective voltage U_{rms} measured previously on the multimeter?

- Calculate the effective current, I_{rms}

-

- Check the rms value of current by measurement on an ammeter.

$I_{rms\ [meas.]}$ =

8.4 Derivation of AC Power

When an AC voltage is applied to an ohmic consumer, the voltage produces an 'in- phase' current (Fig. 8.4.1). The power P produced is given by the product of voltage U and current I. Usually however, the useful or **active power P_{act}** is of interest:

$$P_{act} = U_{rms} \cdot I_{rms} \quad \Rightarrow \quad P = U \cdot I$$

$$\Rightarrow \quad P = \frac{U^2}{R} \quad \Rightarrow \quad P = I^2 \cdot R$$

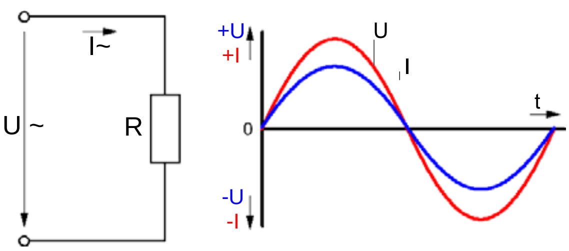


Fig. 8.4.1: Voltage and current, in phase

The active power should always be assumed when P is given without any other details. The suffix 'act' is usually omitted. The **instantaneous power p** is required only in exceptional cases. Here, lower case letters are used:

$$p = u \cdot i \quad \textit{(instantaneous values)}$$

The active power of sine-wave voltages is calculated from the peak values, as follows:

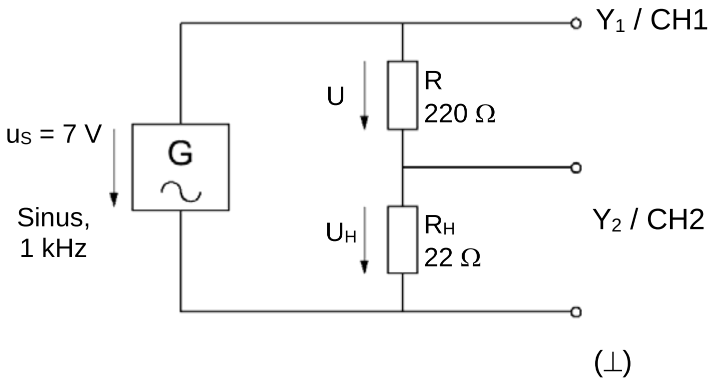
$$P_{actf} = U_{rmsf} \cdot I_{rms} \quad \Rightarrow \quad P_{actf} = \frac{1}{\sqrt{2}} \cdot u_p \cdot \frac{1}{\sqrt{2}} \cdot i_p = \frac{1}{\sqrt{2} \cdot \sqrt{2}} \cdot u_p \cdot i_p = \frac{1}{2} \cdot u_p \cdot i_p$$

The power converted at an ohmic consumer, in AC techniques, is known as the **active power**, because real energy is released and work performed. In contrast, thereis the term 'reactive power' – this will be explained later.

8.5 Active Power of a Sine-wave Voltage in a Practical Exercise

The instantaneous and active values of active power will now be determined by measuring voltage and current on an oscilloscope and drawing the waveforms displayed. An oscilloscope can display only voltages present at its input. Therefore, the current measurement is made, indirectly from the voltage drop across an extra resistor (R_H).

Fig. 8.5.1: Measurement circuit for active power

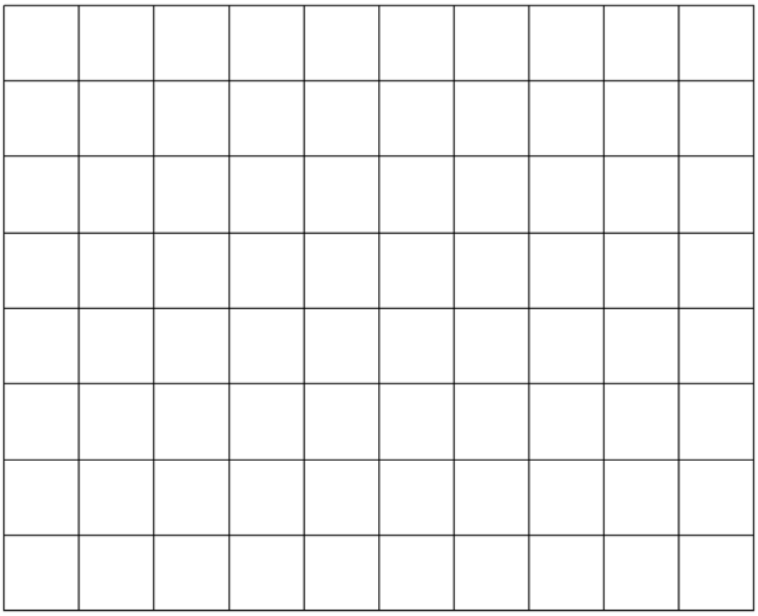


The series circuit in Fig. 8.5.1 uses the fact that the same currentflows through resistors R and R_H. Thus, the voltage drop across R_H represents the magnitude of current and this can be displayed on the oscilloscope. The voltages $U+U_H$ and U_H are connected to channels Y_1 and Y_2. To allow both single voltages U and U_H to be displayed simultaneously, the reference point (Ground), must be connected between the 2 resistors. This is only possible with differential input oscilloscope or multimeter. To display the actual value of U we should subtract the value U_H from the value of $U+U_H$.

- Assemble the circuit in Fig. 8.5.1 on the Electronic Circuits Board. Connect the outputs of the circuit to the channel inputs of the oscilloscope (assembly and measurement details are in Fig. 8.6.1).
- Set the function generator to sine-wave voltage, u_p = 7 V, f = 1 kHz.
- Draw the displayed voltage waveforms $U+U_H$ and U_H (represents I) in the chart (Fig. 8.5.2).

Oscilloscope settings:
X : 0,1 ms / div.
Y_1 : 2 V / div.
Y_2 : 0,5 V / div.

Fig. 8.5.2: Displayed voltage and power waveforms



- Measure, on the waveform drawn, the instantaneous values of u and u_H. Enter the measured values intable 8.5.3.
- From the measured values, calculate the instantaneous values of current, i and power, p. Complete the table with the calculated results.
- Plot the calculated instantaneous values of the power p in the chart (Fig. 8.5.2.) and draw the power curve (extend the y- axis if necessary).

Table 8.5.3.: Instantaneous values, u, u_H, i, p

Time [ms]	$u+u_H$ [V]	u_H [V]	u [V]	i [mA]	p [mW]
0					
0,1					
0,15					
0,25					
0,35					
0,4					
0,5					
0,6					
0,65					
0,75					
0,85					
0,9					
1					

- How much active power is dissipated at resistor, R?

- What is the active power at a resistor of R = 330 Ω, when a symmetrical square-wave voltage u_{pp} = 10 V is applied?

- How much power is dissipated in heat by an ohmic resistor R = 22 Ω, when a symmetrical delta voltage can be seen on an oscilloscope of u_p = 9 V?

8.6 Assembly and Measurements on the Electronic Circuits Board

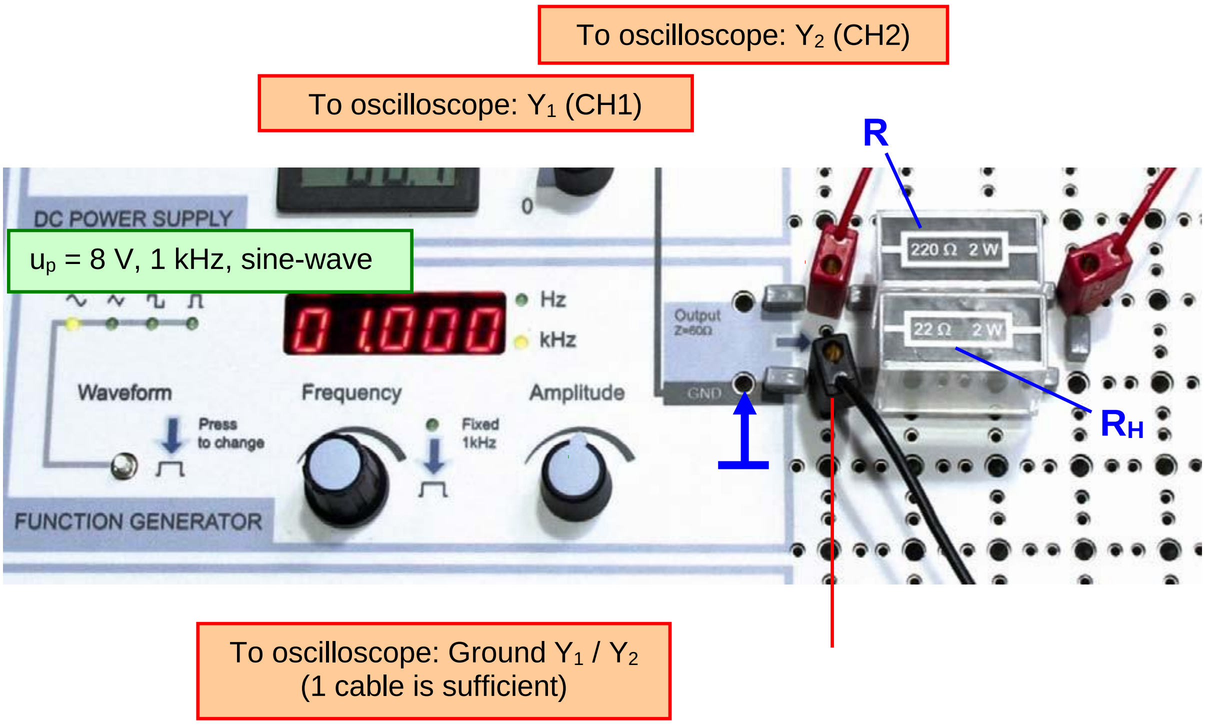


Fig. 8.6.1: Assembly and measurements, Active power, on the Electronic Circuits Board

Experiment (9)

9. Capacitor in an AC Circuit: part1

9.1 Construction and Characteristics of Capacitors

In its simplest form, a capacitor consists of 2 parallel, electrically conductive plates (Fig. 9.1.1, left). An air gap between the plates, acts as an insulator. When a constant voltage U is applied to this capacitor, charge carriers flow between the plates and one plate becomes positively charged, the other negatively charged. As the level of charge increases, an electric field is created between the plates (Fig. 9.1.1, centre). When the voltage across the plates has reached the same as the applied voltage, the flow of current stops.

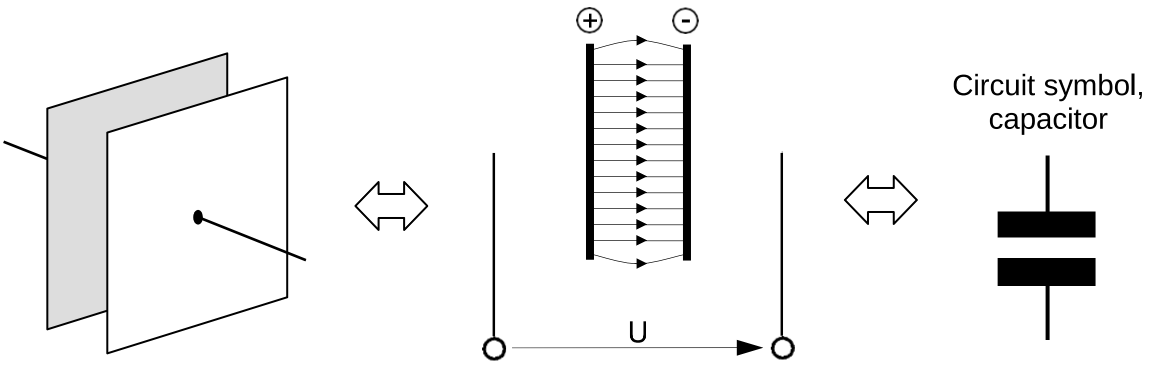


Fig. 9.1.1: Basic construction of a capacitor

The capacitor retains its charge, even when the external voltage is removed. This voltage can be measured at the external connections, on a voltmeter[1]. The amount of the **stored charge Q** depends on the magnitude of the applied **charging voltage U** and the **capacitance C** of the capacitor, i.e.:

$$Q = U \cdot C$$

The **capacitance, C** of the capacitor is determined by its form of construction. The larger the **area of the plates**, the more charge it can store. The smaller the **distance** between the plates, the stronger is the electric field and more charge can be drawn to the plates and stored. Also, the type of insulation between the plates is very significant. This insulation in known as the '**dielectric**'. Some materials support the formation of an electric field between the plates better than others, or than air (free space); these materials have a larger value of dielectric constant ε_r.

The **capacitance, C** is given by:

$$C = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{l}$$

C : Capacitance (Farad)
ε_0 : Absolute permittivity of free space ($8{,}85 \cdot 10^{-12}$ As/Vm)
ε_r : Relative permittivity of the dielectric (dielectric constant)
A : Area of the plates [m^2]
l : Distance between the plates [m]

[1] This measurement is quite difficult using commercial multimeters, because their internal resistance is too small. When attempting to measure the voltage, the capacitor quickly discharges through the R_i of the voltmeter.

When a DC voltage is applied, a charging current flows for only a short time, until the capacitance C of the capacitor is 'filled' with charge carriers. The insulation between the capacitor plates functions as a *break in the DC circuit*. However, if an AC voltage is applied to the capacitor, then the continuous reversal of the polarity of the external voltage results in a continual charge exchange between the plates. This exchange of charge follows the electric field between the plates, that rhythmically changes in strength and direction. An ammeter in the external circuit would indicate the flow of current due to the charge exchange. *For alternating voltages a capacitor does not present any break in the circuit*. However, the flow of alternating current in a capacitor isdifferent to that through an ohmic resistor. There is no dissipation of power at acapacitor! The flow of alternating current in a capacitor is given the term 'reactive current'.

It is logical then, that the resistance offered by a capacitor to the flow of an AC is given the name **capacitive reactance, X_C**. The higher the frequency, f of an applied AC voltage and thelarger the capacitance C of the capacitor, the smaller is the value of X_C. Equation:

$$X_C = \frac{1}{\omega \cdot C} = \frac{1}{2 \cdot \pi \cdot f \cdot C}$$

As shown, the capacitance of a capacitor increases with a smaller distance between the plates. In industrially manufactured capacitors the thickness of the dielectric is microscopic. From this it follows that high demands are placed in the insulation resistance R_p of the dielectric so that any residual current, and thus ohmic losses in the capacitor, is kept as small as possible. In practice, the value of R_p is greater than 1 GΩ.

The thin dielectric also limits the *dielectric strength* of the component. In this respect, a differentiation is made between two characteristic quantities: The **nominal voltage** is the maximum permissible continuous voltage. The **peak voltage** is the maximum permissible short-term transient value of voltage that the capacitor can withstand without causing any damage to the component.

9.2 Types and Tasks of Capacitors

In electrical engineering and electronics, capacitors have a wide variety of uses:

- Storing energy
- Storing data
- Frequency-dependent resistance
- Introducing a phase shift between voltage and current
- Isolating DC and AC voltages
- Smoothing rectified AC
- Construction of delay elements
- Construction of oscillating circuits and filters

Depending on their use, capacitors are required with special properties or distinct characteristic quantities. Table 9.2.1 summarises common types of capacitor construction.

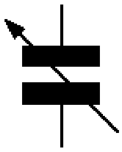
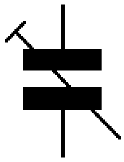
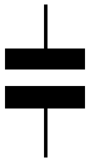
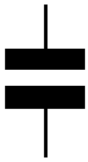
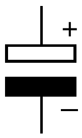
Capacitance	Description	Circuit symbol	Construction	
Variable	Variable capacitor		Capacitance is varied either by: - Plate area - Plate separation or - Dielectric	Precision engineered, intended for frequent, repeated adjustment
	Trimmer			Used seldom or only once, for alignment or tuning processes
Fixed	Ceramic capacitor		Dielectric consists of various ceramic materials (e.g. titanium dioxide, barium titanate) with high dielectric strength and sometimes a higher dielectric constant ε_r (up to 14000)	
	Wound capacitor		Metal and insulating foil (dielectric) are laid out on top of each other and rolled up to give more plate area and thus, a larger capacitance	
	Electrolytic capacitor		The anode (+) is made of metal coated with the insulating dielecric by way of electrolysis. The cathode (-) consists of a paste-like electrolyte. When electrolytic capacitors are used in circuits having a DC component, the correct polarity **must** be observed. **With incorrect connection, there is a danger of explosion!**	

Table 9.2.1: Types of capacitors

9.3 Charge and Discharge of a Capacitor

9.3.1 Principles of Charge and Discharge Processes

By charging / discharging, a capacitor attempts to reach the same value as the external voltage potential present at its terminals. This external voltage could be the output of a voltage source, the output from a votage divider, zero volts (in which case, the capacitor discharges), or any other potential. Charge and discharge current always flow via an ohmic resistor[2], that limits the charge current. In Fig. 9.3.1.1 when S_1 is closed, the capacitor charges via resistor R (U_C = U). When S_1 is opened, the capacitor retains the charge (U_C = constant). When S_2 is closed, the capacitor discharges via resistor R. The capacitor now functions itself as a voltage source. Therefore, the discharge current ($I_{dis.}$) flows in the opposite direction (Fig. 9.3.1.1).

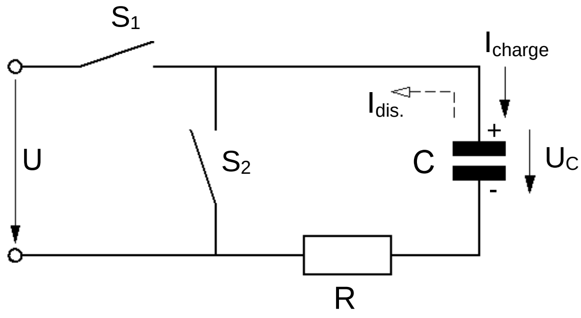


Fig. 9.3.1.1: DC circuit with capacitor C

With a constant charge voltage, the current flow in the circuit and the voltage across the capacitor, follow an **exponential function** (e-function, Fig. 9.3.1.2). The effective**time constant** τ of the curve is given by the product of resistance R in the charge circuit and capacitance C:

$$\tau = R \cdot C$$

C : Capacitance [F]
R : Resistance [Ω]
τ : Time constant [s]

At time 1τ after the start of charging, the voltage at the capacitor (U_C) has reached 0,63 of the maximum value (Fig. 9.3.1.2). After 5-times τ (5τ), the charging process is considered to be finished. The instantaneous value of capacitor voltage u_C is calculated by the equation:

$$u_C = U \cdot \left(1 - e^{-t/\tau}\right)$$

U : Charge voltage [V]
t : Charging time [s]
e : Euler's constant, 2,718

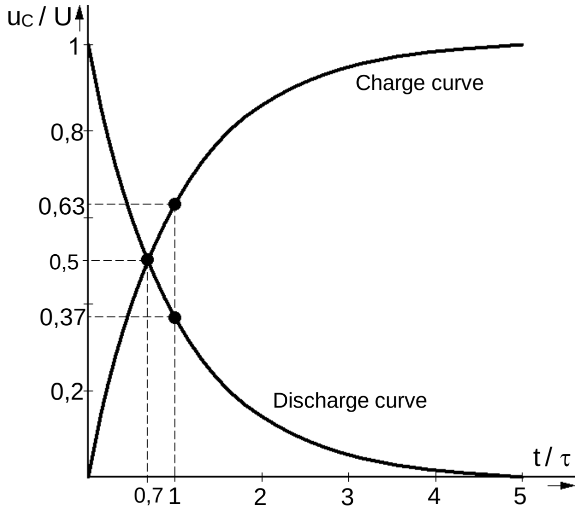


Fig. 9.3.1.2: Charge/discharge curves of a capacitor

The discharge of a capacitor follows the the same e-function (mirrored, Fig. 9.3.1.2). The same time relationships apply as for the charge process: Discharge by 50% after 0,7τ, by 63% (to 0,37·U_C) after 1τ, process end after 5τ. The instantaneous value of capacitor voltage u_C is calculated by the equation:

$$u_C = U \cdot e^{-t/\tau}$$

U : Capacitor voltage [V]
t : Discharging time [s]
e : Euler's constant, 2,718

The flow of current in an RC-circuit, also follows an exponential function $e^{-t/\tau}$ (Fig. 9.3.1.3). The current curves for charge and discharge, are identical. Since the flow of current changesdirection during discharge, the equations for the instantaneous values of current differ in their sign, as given below:

Charge: $i_C = \frac{U}{R} \cdot e^{-t/\tau}$ | U : Charge voltage [V]

Discharge: $i_C = -\frac{U}{R} \cdot e^{-t/\tau}$ | U : Capacitor voltage [V]

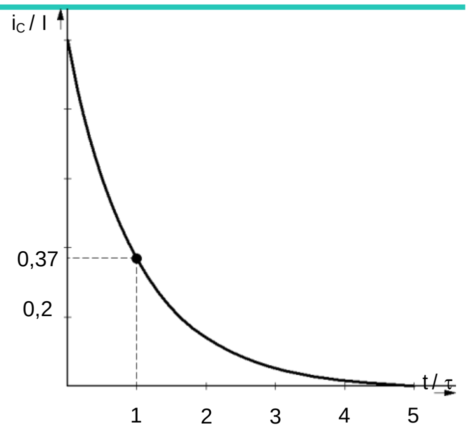


Fig. 9.3.1.3: Charge and discharge current in a capacitor

The charge and discharge response of capacitors is very significant for understanding complex circuits. Here, current, voltage and reactance X_C should be considered together. At the start of charging the flow of current is maximum, whilst at the sametime, the voltage at the capacitor is minimum. Therefore, according to Ohm's law X_C is initially, very small. The current is limited by resistor R in the charging path. Towards the end of charging, at almost maximum capacitor voltage U_C and a small charging current, X_C has increased to a very high value and attempts to increase to infinity (∞). It can be seen already, that current and voltage are out of phase.

- The charging/discharging response of a capacitor will now be examined in an exercise. Assemble the circuit inFig. 9.3.1.4 on the Electronic Circuits Board. If possible, use an analog voltmeter to enable the charging and discharging process at the capacitor to be followed from the deflection of the needle.

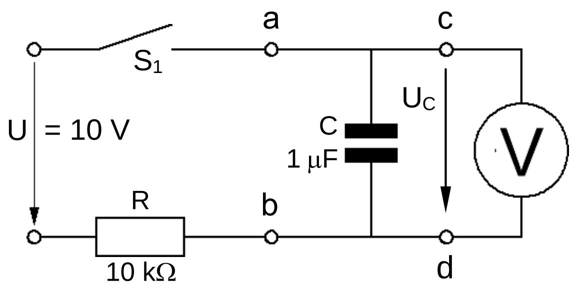


Fig. 9.3.1.4: DC circuit with R and C

- How much time is required by the capacitor C = 1 μF, to charge up to U = 10 V when switch S_1 is closed?

- Now, close the switch and observe the voltage indication. What response do you expect on the voltmeter?

- Open the switch S_1 and observe the indication of the voltmeter. What causes the slow fall of capacitor voltage?

- Assuming the discharge of the capacitor via the test meter, takes 50 s. What is the value of R_i of the voltmeter?

- Now, isolate the charge in the capacitor. Procede as follows:
1. Remove the test meter. 2. Remove the bridge between a and b. – What response is expected of the capacitor?

- Wait one or two minutes. Now, measure the capacitor voltage U_C. What initial value do you expect?

- Calculate the value of charge current at the instant of closing switch S_1 (with a fully discharged capacitor C).

- Is it possible to check this value by measurement on an ammeter (multimeter)?

9.3.2 Reaction of a Capacitor to Square-wave Voltages

A square-wave voltage with a positive amplitude can be considered as a DC voltage, periodically switched on and off (U in Fig. 9.3.2.1 right). If the pulse duration and interpulse period are both at least equal to $5 \cdot \tau$, then the capacitor C can fully charge anddischarge, via resistor R (Fig. 9.3.2.1 left). This results in the typical voltage response across the capacitor C, of a sequence of e-functions (U_C in Fig. 9.3.2.1 right).

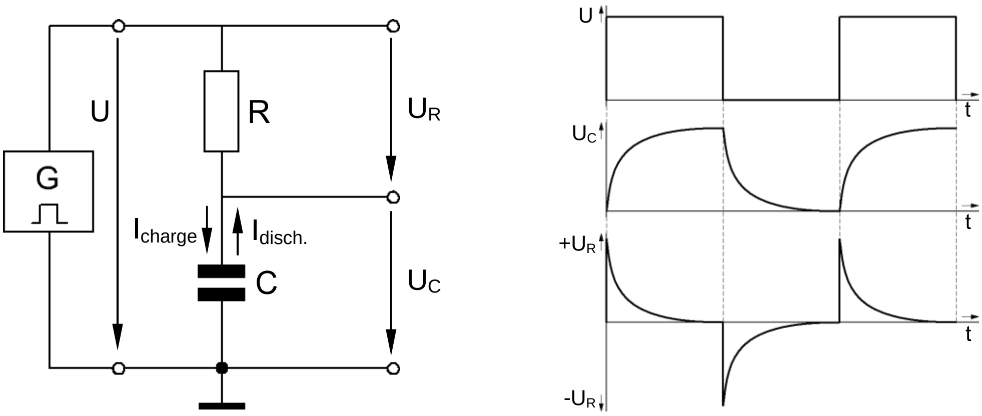


Fig. 9.3.2.1: Reaction of a capacitor to a square-wave voltage

Whilst the capacitor is charging, the voltage difference $U_R = U - U_C$ is dropped across the ohmic resistance. The reason for U_R is the initial maximum, then quickly reducing charging current I_{charge}. For the time of charging, a typical needle pulse (e-function) across R, can be displayed on an oscilloscope. The shorter the time constant $\tau = R \cdot C$, the narrower is the needle pulse.

During the interpulse period, the capacitor C functions as a voltage source, discharging via R with a current flow in the opposite direction ($I_{dis.}$). The discharge occurs with the same time constant τ, so that the second needle pulse produced has the same shape as the first pulse. Due to the current reversal, this needle pulse is negative.

The needle pulses produce heat losses at resistor R. Here, actual ohmic power is dissipated, so-called 'active power'. In contrast, at the capacitor there is only reactive power that does not produce any warming effects.

The response of a capacitor will now be examined using the components shown, together with the input voltage given inFig. 9.3.2.2.

- Assemble the circuit in Fig. 9.3.2.2 on the Electronic Circuits Board.
- Set the square-wave generator to a peak voltage of $U_p = 4$ V at a frequency of f = 500 Hz.

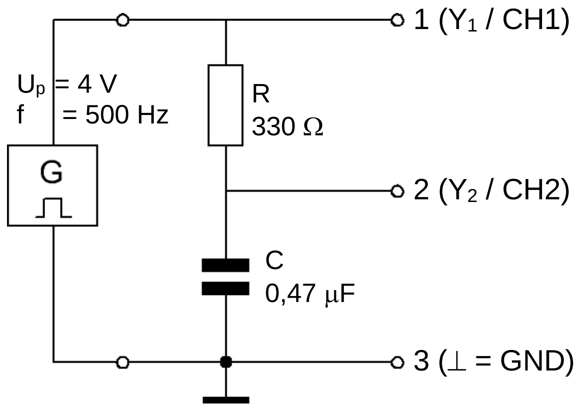
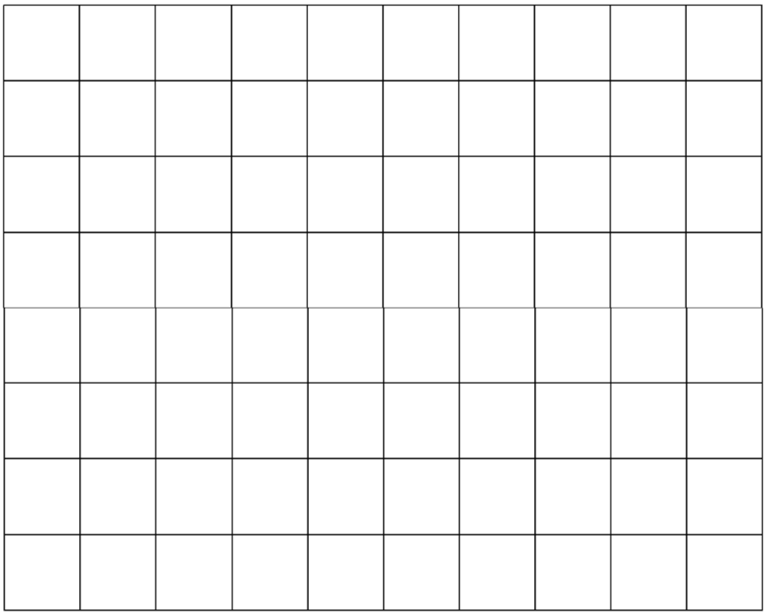


Fig. 9.3.2.2: Square-wave voltage in an RC-circuit

- Connect the oscilloscope as shown. Select the settings on the oscilloscope so that both signals are displayed (one below the other) and a time base to display at least one complete signal period.
- Draw the signals displayed U and U_C in the chart in Fig. 9.3.2.3.

Fig. 9.3.2.3: Display, U and U_C



Oscilloscope settings:
X : 0,2 ms/ div.
Y_1 : 2 V/ div., DC
Y_2 : 2 V/ div., DC

- Change the connections of the oscilloscope inFig. 9.3.2.2, to display the signal across resistor R.
- Draw the signals displayedU and U_R in the chart in Fig. 9.3.2.4.

Oscilloscope settings:
X : 0,2 ms/ div.
Y_1 : 2 V/ div., DC
Y_2 : 2 V/ div., DC

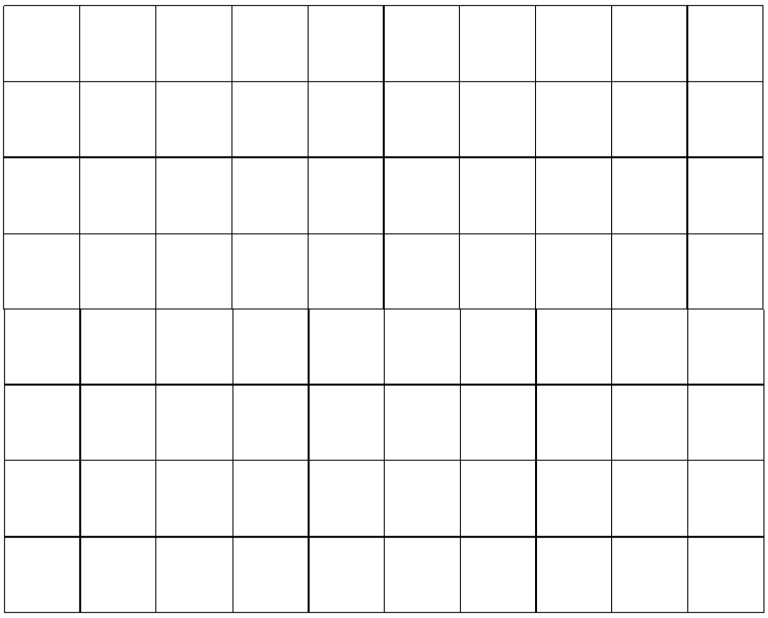


Fig. 9.3.2.4: Display, U and U_R

- From the waveforms drawn, determine the time constant τ as accurately as possible. Check your result by calculation.

τ From waveforms:

τ By calculation:

- What is the voltage at the capacitor (u_C) 0,4 ms after the start of charging? Measure the value from the waveforms or on the oscilloscope screen. Check your measurement by calculation.

  u_C Measured after 0,4 ms :

  u_C Calculated:

- What current is flowing 0,2 ms after the capacitor starts discharging? Determine the current from the waveforms drawn in Fig. 8.3.2.4 or directly from the oscilloscope screen. Check your measurements by calculation.

  $i_{dis.}$ After 0,2 ms:

  $i_{dis.}$ Calculated:

- At what time does the capacitor store its maximum charge and how large is this maximum charge?

- In the circuit of Fig. 9.3.2.2 the capacitor C is replaced with one of C = 1 μF. What effect has this change in the circuit?

- Check your statement by measurement. Display the voltage across the capacitor C = 1μF (R unchanged).

9.4 Capacitor with a Sine-wave Voltage

9.4.1 Phase Shift between Current and Voltage

It has already been seen that with a square-wave voltage applied to a capacitor, current and voltage at the capacitor, are out of phase. The current immediately reaches a fairly high value, whilst in comparison, the voltage gradually increases as the capacitor is charged. In other words, the current leads the voltage.

With a sine-wave voltage applied, the capacitor charges in rhythm with the periodic time T from a positive to a negative peak value (U_C in Fig. 9.4.1.1). The current leads this process by a quarter-period (I_C in Fig. 9.4.1.1). The current is at a maximum when the voltage has just cut the zero axis. The phase shift between current and voltage is 90°.

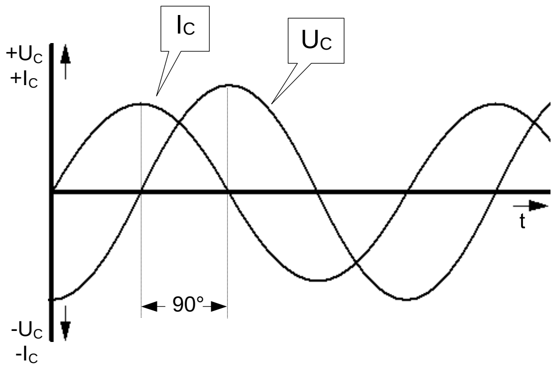
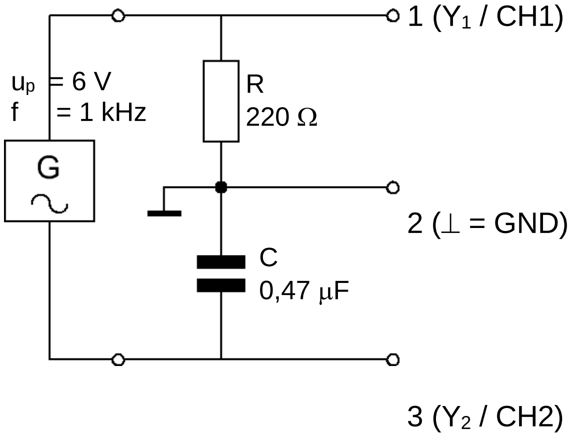


Fig. 9.4.1.1: Phase shift between current and voltage at a capacitor

The phase shift between current and voltage will now be proved in a circuit as shown in Fig. 9.4.1.2.

- Assemble the circuit in Fig. 9.4.1.2 on the Electronic Circuits Board.

Fig. 9.4.1.2: Exercise circuit to show the phase shift between I and U



Since the changes of current and voltage at an ohmic resistor are always proportional to each other, U_R (Y_1 / CH1) can be used for showing the phase of the current I_C in the circuit.

- Set the signal generator to a sine-wave voltage $u_{pp} = 12$ V at a frequency of f = 1 kHz.
- Connect the 2-channel oscilloscope as shown in Fig. 9.4.1.2.

By adjusting the 0-axis (GND) between R and C, the voltages U_R and U_C can both be displayed on the 2-channel oscilloscope. However, the negative voltage U_C (Y_2 / CH2) has a 180° phase shift. For measuring the correct phase relationship, one channel of the oscilloscope must be operated in the 'inverted' mode.

- Display the voltage waveforms U_R and U_C on the oscilloscope. Adjust the oscilloscope for a display of least 2 periods of the sine-wave.
- Draw the signal waveforms displayed in the chart, Fig. 9.4.1.3.

Oscilloscope settings:
X : 0,1 ms/ div.
Y_1 : 1 V/ div., AC
Y_2 : 2 V/ div., AC, inverted

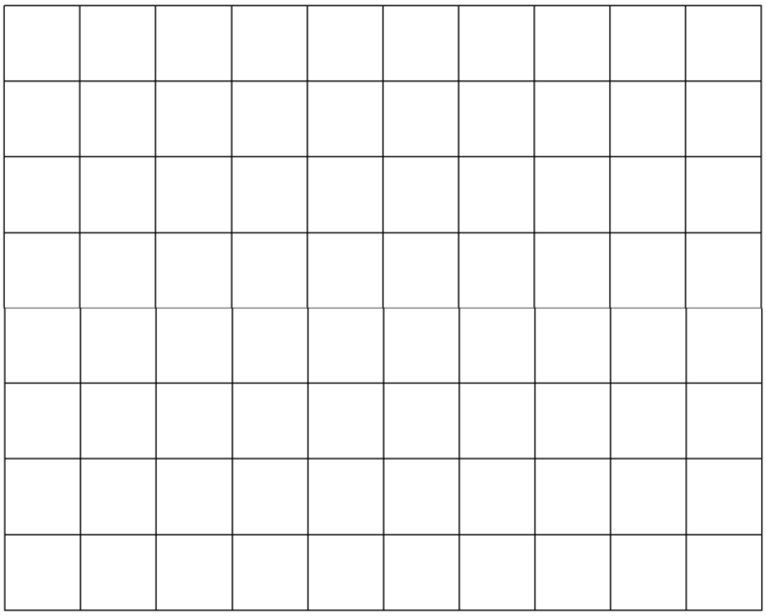


Fig. 9.4.1.3: Phase relationship between current voltage at the capacitor

- From the signal waveforms, measure the periodic time T, the frequency f and the angle of phase shift φ between current and voltage.

9.4.2 Capacitive Reactance, X_C

When a sine-wave voltage is applied to a capacitor, the capacitor is continually

charged and discharged. This corresponds to a periodic build-up and decay then a build-up with the opposite polarity, of the electric field between the plates of the capacitor. The current flowing at this time, leads the voltage by 90° and determines the physical properties of the capacitor as a resistance, that limits the flow of current. Since at this resistor, there is no thermal power dissipated, it is known as '**capacitive reactance, X_C**.

The magnitude of the capacitive reactance X_C is inversely proportional to the capacitance C of the capacitor and the frequency f of the applied sine-wave voltage. Equation:

$$X_C = \frac{1}{2 \cdot \pi \cdot f \cdot C}$$

C : [F]
f : [1/s]
X_C : [Ω]

With a given capacitor current I_C and a known capacitor voltage U_C, Ohm's law can be used for calculation. Equation:

$$X_C = \frac{U_C}{I_C}$$

U_C : [V]
I_C : [A]
X_C : [Ω]

The response of the capacitive reactance X_C will now be examined using the circuit shown in Fig. 9.4.2.1. The current flowing in the capacitor can be calculated from the voltage drop U_R across the resistor R = 1 kΩ (U_R and I_C in phase).

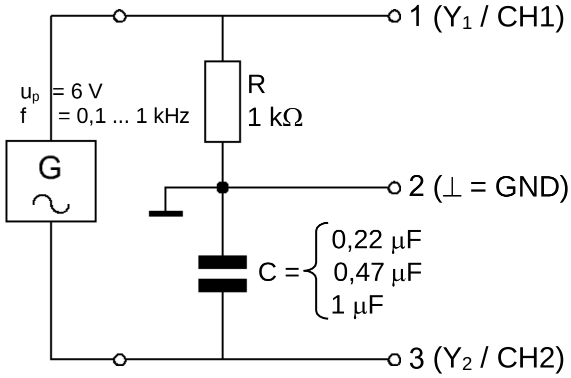


Fig. 9.4.2.1: Exercise circuit to examine the relationship between X_C, f and C

By adjusting the 0-axis (GND) between R and C, the voltages U_R and U_C can both be displayed on the 2-channel oscilloscope.

- Assemble the circuit in Fig. 9.4.2.1 on the Electronic Circuits Board.
- Set the signal generator to a sine-wave voltage u_{pp} = 12 V at an initial frequency of f = 1 kHz.
- Connect the 2-channel oscilloscope as shown in Fig. 9.4.2.1.
- Measure the peak-to-peak values of the voltages U_C and U_R for the 3 capacitors listed in table 9.4.2.2, at the given frequencies. Enter the measured values in table 9.4.2.2.

Table 9.4.2.2: Capacitive reactance X_C for different capacitors at various frequencies

f [kHz]		0,1	0,2	0,3	0,4	0,6	1
U_C [V_{pp}]	0,22 µF						
	0,47 µF						
	1 µF						
U_R [V_{pp}]	0,22 µF						
	0,47 µF						
	1 µF						
I_C [mA_{pp}]	0,22 µF						
	0,47 µF						
	1 µF						
X_C [kΩ]	0,22 µF						
	0,47 µF						
	1 µF						

- Calculate the peak-to-peak currents I_C and enter the values in table 9.4.2.2.
- Calculate the values of X_C and enter the values in table 9.4.2.2.
- Plot the calculated values of capacitive reactance X_C in the chart (Fig. 9.4.2.3). Join the points plotted and draw the characteristics X_{Cn} = f(f) for the 3 capacitors.

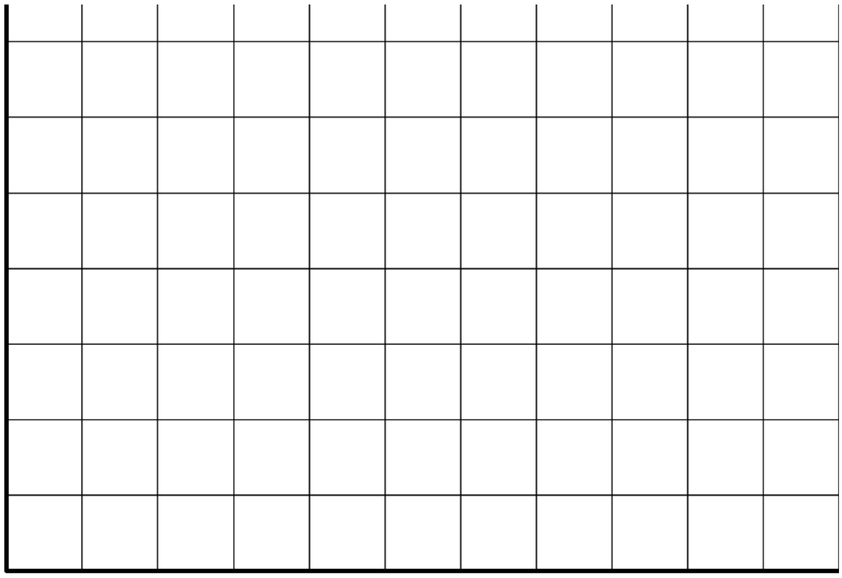


Fig. 9.4.2.3:
Characteristics $X_C = f(f)$

- Check the values measured for X_C = f (100Hz) for the capacitor C = 0,47 µF by calculation.

- How do you explain the deviation between measured and calculated values for X_C = f(100 Hz ; 0,47 µF)?

- What tendency is shown by the capacitive reactance X_C of a capacitor C = 0,01 µF (= 10 nF) at very high (> 1 MHz) and very low (< 100 Hz) frequencies?

- What value must a capacitor have, to present a capacitive reactance of X_C = 50 Ω at a frequency of f = 14,5 kHz? Check your calculated result by measurements, using the circuit in Fig. 9.4.2.1.

Experiment (10)

10. Capacitor in an AC Circuit: part 2

10.1 Active and Reactive Power at a Capacitor

In an *ideal capacitor,* there is no **active power** in the form of dissipated heat. But there is a flow of energy between the capacitor plates in the form of charge carriers that the capacitor stores as a voltage which can be measured, or as an electric field between the plates (Fig. 9.1.1). With a later discharge or a reversal of charge, this energy in the capacitor, is again available. The electric field decays and drives the discharge current. Thus, current and voltage at a capacitor, produce only a **reactive power.**

In real capacitors however, there are *ohmic losses* that must be taken into account. On the one hand, there is the frequency-dependent **leakage current** through the dielectric, which like all insulators, does not have an infinitely large resistance. Leakage currents are responsible for a slow discharge of the energy stored in the capacitor. In practice, these losses are more significant in electrolytic capacitors that have a measurable insulation resistance due to their form of construction. This is more apparent on old electrolytic capacitors, where the leakage current is higher. In applications where a capacitor is used for storing information, the very minute leakage currents must also be taken into account, because they limit the length of time that the data can be stored. For all other circuits, the second form of ohmic loss, the frequency-dependent **displacement current**, is significant. The dielectric supports the build-up of the electric field and in this way, increases the capacitance of the capacitor. This is achieved whereby the polarity of the molecules in the dielectric material is reversed intime with the frequency. The higher the frequency, the more often are the polarity changes in the dielectric and the higher the flow of displacement current, and the greater is the power consumed by the electric field. Thus, at high frequencies, the warming of a capacitor can be physically felt.

The active power losses are combined and represented by the **power loss resistance R_p** imagined to be connected in parallel to the capacitor (Fig. 10.1.1), through which the sum of all leakage currents flow I_{Rp}. Since the capacitor current I_C leads the leakage current I_{Rp} by 90°, the relevant vectors show a loss angle, δ (Fig. 10.1.1).

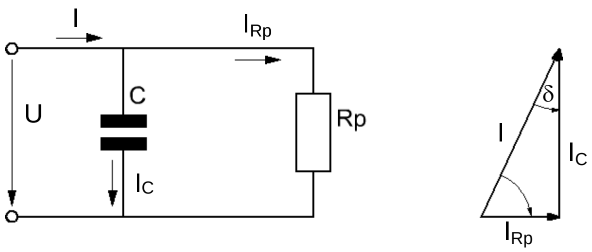


Fig. 10.1.1: Losses at a capacitor

The active powerlosses give the **loss factor d**, that should beas small as possible (< 1):

$$d = \tan\delta = \frac{I_{Rp}}{I_C} = \frac{X_C}{R_p}$$

d : Loss factor, [no dimensions]
δ : Loss angle [°]
I_{Rp} : Leakage current [A]
I_C : Reactive current [A]
X_C : Reactance [Ω]
R_p : Loss resistance [Ω]

The active power consumed by a capacitor is the result of unwanted but unavoidable losses. They must be accepted within reason, due to the physical limits in the manufacture of capacitors.

The **reactive power Q** at a capacitor is given by the reactive current and the capacitor voltage. It can be represented as a multiplication of the instantaneous values of i_C and u_C in a line chart, with the phase relationships (Fig. 10.1.2).

The reactive power Q is calculated from:

$$Q_C = U_C \cdot I_C \quad \text{or}$$

$$Q_C = \frac{U_C^2}{X_C} \quad \text{or}$$

$$Q_C = I_C^2 \cdot X_C$$

Q_C: Reactive power, [Ω]
U_C: [V]
I_C : [A]
X_C: [Ω]

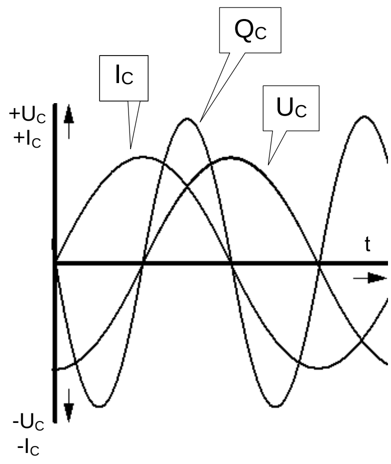


Fig. 10.1.2: Reactive power

In an example circuit, the response of current and voltage will be displayed on an oscilloscope, for one complete period of a sinusoidal voltage. The waveforms displayed will then be drawn in a chart. Finally, the waveform of the reactive power curve will be plotted from the values measured and the curve drawn in the chart.

Assemble the circuit in Fig. 10.1.3 on the Electronic Circuits Board.

The current I_C is determined from the voltage U_R measured on Y_1 / CH1 of the oscilloscope. For measuring the correct phase relationship, one channel of the oscilloscope must be operated in the 'inverted' mode.

- Set the signal generator to a sine-wave voltage u_{pp} = 10 V at a frequency of f = 1 kHz.
- Connect the 2-channel oscilloscope as shown in Fig. 10.1.3.
- Display the voltage waveforms U_R and U_C on the oscilloscope.

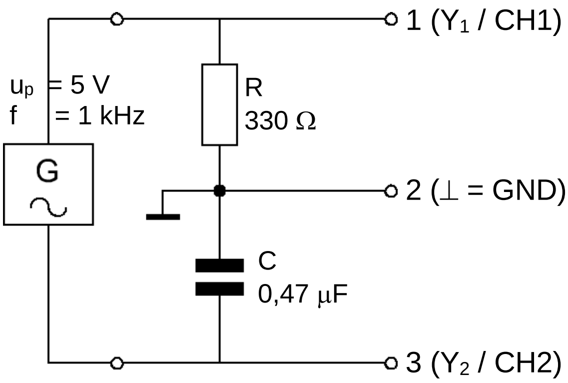


Fig. 10.1.3: Exercise circuit for measuring the capacitive reactance, Q_C

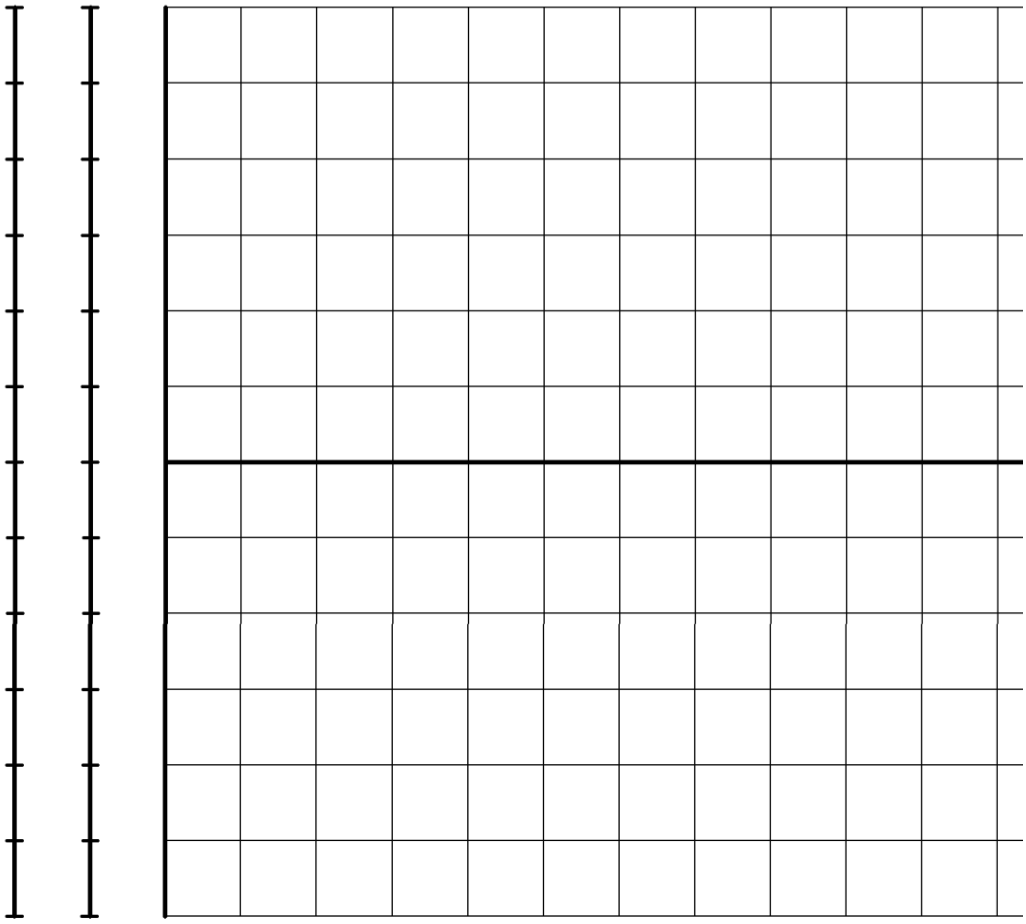
- Measure the instantaneous values of the voltages u_R and u_C at the times given in table 10.1.4. Enter the values in the table.
- Calculate the instantaneous values of capacitor current i_C from u_R and enter the values in the table.
- Calculate the reactive power q_C from u_C and i_C, at the times given in table. Complete the table with your results of calculation.

Table 10.1.4: Instantaneous values, exercise circuit in Fig. 10.1.3

t [ms]	**0**	**0,1**	**0,2**	**0,25**	**0,4**	**0,5**	**0,6**	**0,75**	**0,8**	**0,9**	**1**
u_R [V]											
u_C [V]											
i_C [mA]											
q_C [mW]											

- Sketch the current curve $I_C = f(t)$, the voltage curve $U_C = f(t)$ and the power curve $Q_C = f(t)$, as accurately as possible, in the chart given in Fig. 10.1.5).

Fig. 10.1.5: Voltage U_C, reactive current I_C and reactive power Q_C waveforms at the capacitor



10.2 Capacitors Connected in Series

Response of Capacitors Connected in Series

In a **series connection** of capacitors, the *plate separation* l (Fig. 10.2.1) is effectively increased. The total capacitance is therefore, less than the smallest single capacitor. Equation:

$$C_{tot} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots + \frac{1}{Cn}}$$

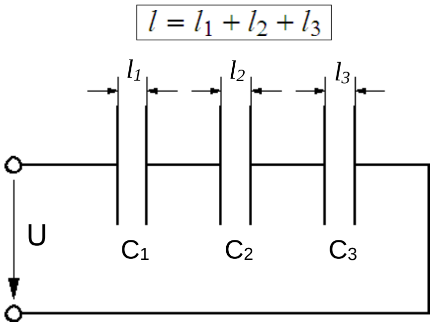
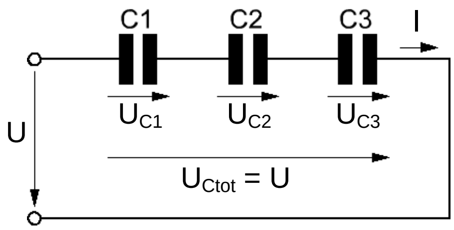


Fig. 10.2.1: Series connection of capacitors

With only 2 capacitors connected in series, the equation simplifies to:

$$C_{tot} = \frac{C_1 \cdot C_2}{C_1 + C_2}$$

Fig. 10.2.2: Series connection of capacitors



The same current flows through all capacitors and the individual voltages across the capacitors, add to give the total voltage U. In some applications, this is referred to as a **capacitive voltage divider** (Fig. 10.2.2).

$$U = U_{tot} = U_{C1} + U_{C2} + U_{C3} + \ldots + U_{Cn}$$

Similarly, at a given freqency f, the total reactance X_{Ctot} is given by:

$$X_{Ctot} = X_{C1} + X_{C2} + X_{C3} + \ldots + X_{Cn}$$

10.2.1 Practical Proof of the Capacitor Response in a Series Circuit

The statement, 'the total capacitance of a series circuit is always less than the smallest single capacitor', will now be proved by voltage and indirect current measurements on a multimeter.

- Assemble the circuit in Fig. 10.2.1.1 on the Electronic Circuits Board.
- Set the function generator to U_{rms} = 4 V, f_{Sine} = 1 kHz.
- Measure the values listed in table 10.2.1.2 with a voltmeter and enter the values in the table.

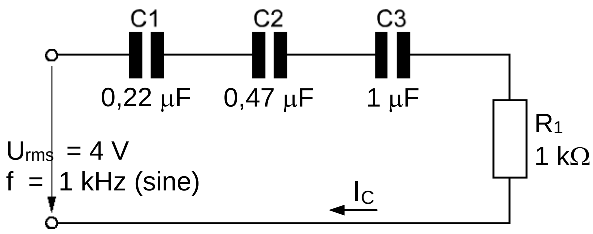


Fig. 10.2.1.1: Measurements on a series circuit of capacitors

Table 10.2.1.2: Measurements on a series circuit of capacitors

All voltages in [V]					
U_{rms}	U_{C1}	U_{C2}	U_{C3}	U_{Ctot}	U_{R1}

- From the measured values and using Ohm's law, calculate first the capacitor current I_C, and then the reactance's X_{Cn} and X_{Ctot}.

- Calculate the individual capacitances C_n and the total capacitance C_{tot}. Use the calculated values of reactance.

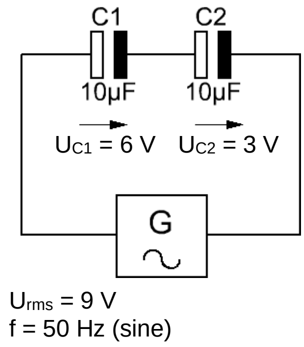
- Check the flow of alternating current I_C on an ammeter. Compare the measured and calculated values.

- Calculate C_{tot} as a check, using the nominal values of the 3 capacitors.

In the circuit of Fig. 10.2.1.3, a fault has occurred in the voltage distribution between the capacitors. What could have been the cause?

- What is the value of C_{tot} in a faulty circuit as in Fig. 10.1.2.3?

Fig. 10.2.1.3: Series circuit, 2 equal value electrolytic capacitors



10.2.2 Exercise Assembly of a Capacitor Series Circuit on the Electronic Circuits Board

An output voltage is set on the function generator of the Electronic Circuits Board of U_{rms} = 4 V at a frequency of f = 1 kHz (Fig. 10.2.2.1). The voltage divider of R_1 and capacitors C_1, C_2, C_3 is arranged so that the voltmeter cam measure each individual voltage, without any hinderance. The voltage U_{Ctot} = 3,07 V is measured across the 3 capacitors. For a check measurement of the current, the ammeter can beinserted in the circuit in place of one of the bridges to the generator connections.

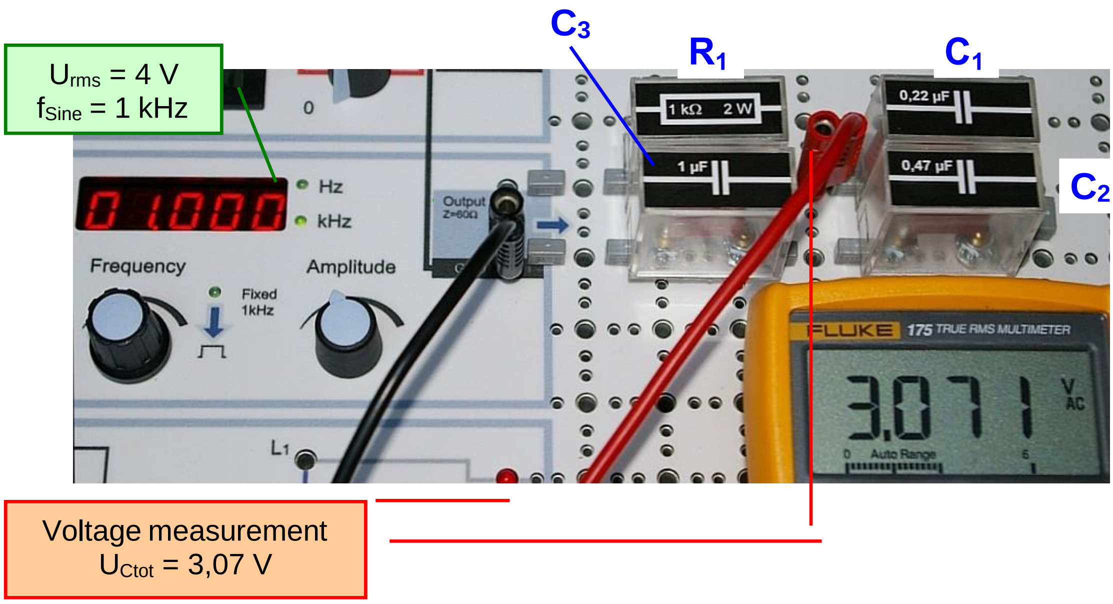


Fig. 10.2.2.1: Exercise assembly for the series connection of capacitors

10.3 Capacitors Connected in Parallel

10.3.1 Response of Capacitors Connected in Parallel

In a **parallel circuit** of capacitors, the *plate area A* becomes larger. Therefore, the capacitance C is given by the sum of all single capacitors

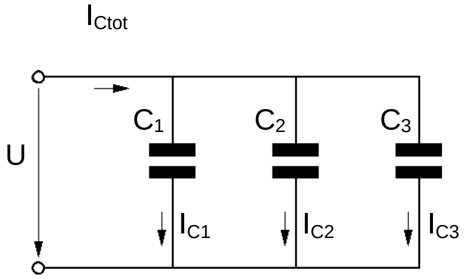


Fig. 10.3.1.1: Parallel circuit of capacitors

Equation:

$$C_{tot} = C_1 + C_2 + C_3 + \ldots + C_n$$

The total current I_{Ctot} is divided between the individual capacitor branches, according to the values of the individual capacitors.

The capacitor voltage U_C across all parallel connected capacitors, is the same. The capacitive reactance of the whole circuit, X_{Ctot} is less than the smallest single reactance, X_{Cn}.

$$X_{C_{tot}'s} = \frac{1}{\frac{1}{X_{C1}} + \frac{1}{X_{C2}} + \frac{1}{X_{C3}} + \ldots + \frac{1}{X_{Cn}}}$$

10.3.2Practical Proof of the Capacitor Response in a Parallel Circuit

The statement, 'the total capacitance of a parallel circuit of capacitors is equal to the sum of the single capacitances' will now be proved by voltage and current measurements on a multimeter.

- Assemble the circuit in Fig. 10.3.2.1 on the Electronic Circuits Board.
- Set the function generator to U_{rms} = 4 V, f_{Sine} = 1 kHz.
- Measure the voltage U and the total current I_{Ctot}.

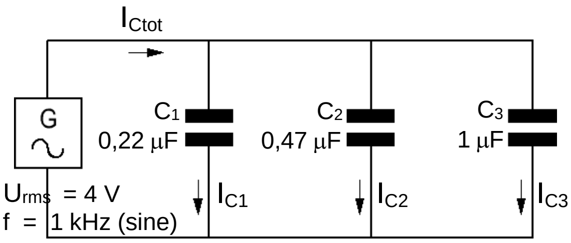


Fig. 10.3.2.1: Measurements on a parallel circuit of capacitors

U = ... ; I_{Ctot} = ...

- Calculate the total capacitance of the parallel circuit using the measured values.

- As a check, calculate the capacitor values from their nominal valus and compare the result with the value of C_{tot} calculated from the measured values.

Experiment (11)

11 Coil in an AC Circuit

12.1 Construction and Characteristics of Coils

Current flowing through a conducting material (e.g. copper wire), generates a *magnetic field*, the *lines of force* of which can be considered as concentric circles about the center of the wire (Fig. 11.1.1). The term 'magnetic field' is often used (and is also used in this handbook), but strictly speaking, the real term is **magnetic flux density B** or **magnetic induction**. The direction of the magnetic flux ('lines of force') around the wire is given by the *right-hand rule*: If the thumb of the right-hand points in the direction of the current flow, then the fingers bent around the wire, point in the direction of the magnetic flux.

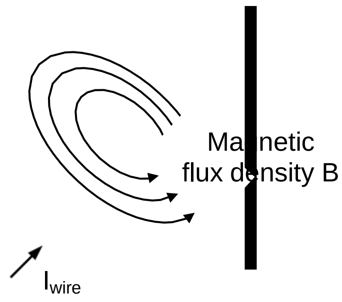


Fig. 11.1.1:

Magnetic flux density B

A coil is created when a conductor is wound to form a spring-like body. The shape of the coil causes a concentration of the magnetic flux B. Fig. 11.1.2 shows the orientation of the magnetic flux in and around, a cylindrical coil of wire. In electronic circuits, either of the circuit symbols shown in Fig. 11.1.2 right, can be used. The top symbol is used mainly for high-energy, low frequency applications (e.g., electric motors or transformers); the symbol below this, is used in applications for higher frequencies with a lower power (e.g., oscillatory circuits or small coupling transformers).
Coils react to a change in current flow that causes a build-up or decay of their magnetic field. The reaction is always opposite to the cause, thus:

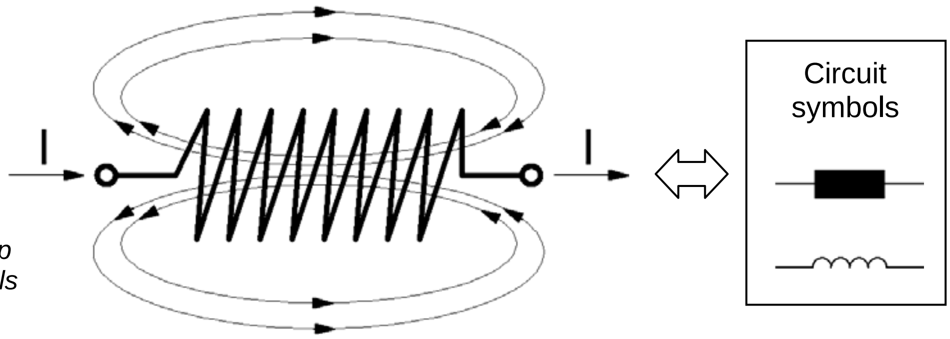


Fig. 11.1.2: Field build-up and circuit symbols of coils

- An increase in current produces a **mutual induction U_L** in the coils that opposes the external voltage. This voltage cannot be measured, but it has the effect on the current, of producing a decay of the magnetic field. The coil consumes energy from the circuit to build up the magnetic field, that the coil stores as magnetic flux.
- If the current in a circuit decrease, then the coil generates a voltage by mutual induction that attempts to maintain the current flow. In other words, it 'pushes' current into the circuit. The energy for this process originates from the magnetic field, that in turn, decays by the same amount.

The reaction of a coil to changes in the current, depends on its **inductance L**. The larger the inductance, the greater is the effect of the mutual induction of the coil in the circuit. The inductance L is given by the properties of the coil, *number of turns*, *cross sectional area and length of the coil*, *and material* of the conductor.

A decisive factor is also whether the coil is air-spaced or has a *core* in the center, the material of which supports the magnetic flux. An example is shown in Fig. 11.1.3, a small so-called cross-wound coil for high frequency applications in the region of 300 to 3000 kHz. It is wound on aplastic former with an iron-dust core in the center. By screwing the core in or out, the inductance of the coil can be altered for the purposes of tuning.

Fig. 11.1.3:
Example of a cross-wound coil

In the calculation of inductance, the number of windings is taken as a square of the number. The other terms or factors, in the equation can only be approximately estimated. Therefore, these factors are combined to give the **coil constant A_L**.

Inductance:

$$L = N^2 \cdot A_L$$

L : Inductance, Henry [H]
N : Number of windings [no dimensions]
A_L : Coil constant [H]

Coil constant:

(Cylindrical coil)

$$A_L = \frac{\mu_0 \cdot \mu_r \cdot A}{l}$$

A : Cross-sectional area [m^2]
l : Length [m]
μ_0 : Magnetic field constant $1{,}257 \cdot 10^{-6}$ [Vs/Am]
μ_r : Permeability [no dimensions]

For a *cylindrical* coil, the coil constant A_L is valid with the above equation. Determining the magnitude of A (cross-sectional area) and l (length), depends on whether the coil has a core or not:

- *Without a core,* the area and length refer to the actual coil. Also, the permeability number μ_r is omitted from the equation.

- *With a core,* the area and length of the core as well as the permeability number μ_r for the material, must be inserted in the equation.

The permeability number μ_r in a vacuum is unity ('1'), with air, almost unity and increases when special core materials are used, up to a 6-figure value.

Due to the effects of mutual induction in the coil, *alternating currents* produce an **inductive reactance X_L**, where no active power is dissipated. The coil does consume energy however, from the circuit for the build-up of the magnetic field, but with the later decay of the field, feeds this energy back into the circuit.

The magnitude of the inductive reactance depends on the frequency and the inductance; equation:

$$X_L = \omega \cdot L = 2\pi \cdot f \cdot L$$

X_L : Inductive reactance [Ω]
ω : Angular frequency [1/s]
f : Frequency [1/s]
L : Inductance [H]

12.2 Types and Tasks of Coils

In electrical engineering and electronics, coils are required in a multitude of very different applications:

- Energy storage
- Electric drives (electromotors)
- Converting other forms of energy to electrical energy (generators)
- Transformation of AC voltages and current (transformers)
- Isolating electrical circuits (coupling transformers)
- Switching large currents by way of a smaller current (relays, contactors)
- Selection of frequency ranges (filters)
- Generating oscillations (oscillatory circuits)

Table 11.2.1 Summary of basic types of coils and applications.

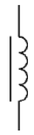
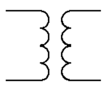
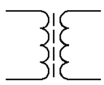
Inductance	Description	Circuit symbol	Construction
Variable	Adjustable inductance		For single or seldom alignment processes(high frequency techniques)
Fixed	Fixed inductance		Coil without core, air-spaced, wound on a former or encapsulated; $\mu_r \sim 1$
	Coil with core		Coil with core for improving the magnetic flux by increasing the inductance; $\mu_r \neq 1$
	Transformer	 	Two coils (primary & secondary windings), coupled via a common magnetic field; the transformation of energy is determined by the ratio of the coil windings. For low-frequency uses; for energy transfer, always with core, for high-frequency uses, also without core.

Table 11.2.1: Types of coils

12.3 Reaction of a Coil to Voltage Changes

On and Off Switching Processes at a Coil

The current in a coil change only when the current is switched on and off. The change produced in the magnetic flux generates a *self-induced e.m.f. (or voltage)*. Its direction is such that it maintains the existing state of the magnetic field. When the current is switched on, the self-induction effect then opposes the build-up of the magnetic flux. At the instant of switch-on, the mutually induced voltage opposes the input voltage, thus there is no flow of current. With the initial rapid increase in current flow, the magnetic field in the coil increases and the effects of mutual induction are reduced. Finally, the current in the circuit is limited by the ohmic resistance of the coil, or any other resistor in the circuit. (Fig. 11.3.1.1).

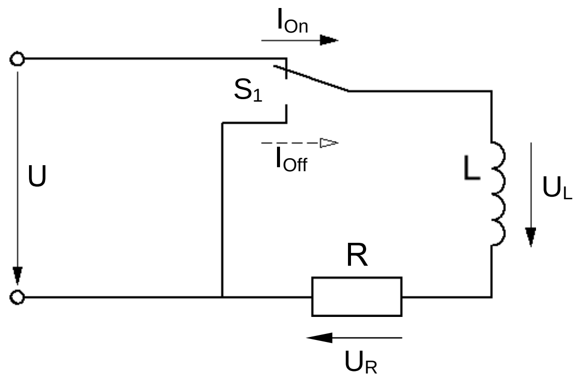


Fig. 11.3.1.1: DC circuit with coil, L

Current and voltage at the coil, both follow an *e-function* (Fig. 11.3.1.2 shows the current curve). The same applies to the switch-off process. At the instant of switching off, an opposing self-induced voltage delays the decay of current. The field energy in the coil, drives the current in the same direction, through the circuit. The decay of current follows a similar e-function as before (Fig. 11.3.1.2). Finally, both coil and resistor are without voltage and there is no flow of current; the field energy in the coil is converted at the resistor, to heat.

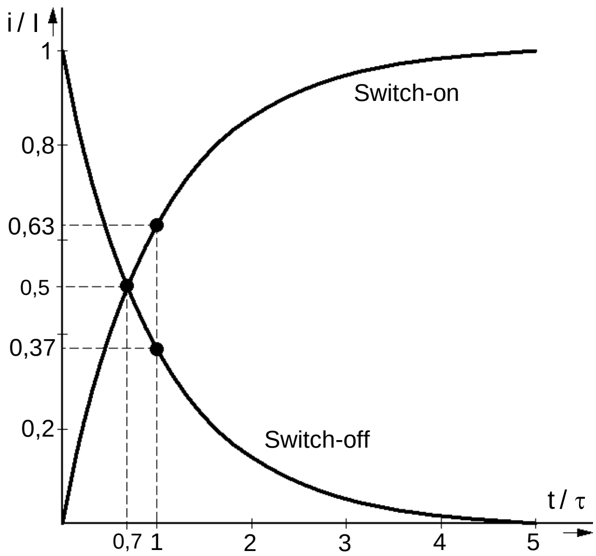


Fig. 11.3.1.2: On and Off switching curves at the coil

The time response of a coil, corresponds to that of a capacitor. The time constant τ is given by the ratio of inductance L to resistance R:

$$\tau = \frac{L}{R}$$

L: Inductance [H]R: Resistance [Ω]
τ: Time constant [s]

At 1·τ after switch-on, the current in the coil has reached 0,63-times its maximum value (Fig. 11.3.1.2). After 5·τ, the field build-up is complete and the current flow is at maximum.

The instantaneous value of current i_L in the coil, is given by:

$$i_L = I_{\max} \cdot \left(1 - e^{-t/\tau}\right)$$

I_{max}: U/R [A]
t : Switch on time [s]
e : Euler's number: 2,718

The decay of coil voltage U_L after switch-on, is given by:

$$u_L = U \cdot e^{-t/\tau}$$

U: Maximum coil voltage [V]

The decay of current after switch-off, follows a mirrored e-function (Fig. 11.3.1.2). The same time relationships apply as for the switch-on process: Current decays by 50% after 0,7·τ; by 63% (to 0,37·I_{max}) after 1·τ; process end after 5·τ.

The instantaneous value of current i_L in the coil, is given by:

$$i_L = I_{max} \cdot e^{-t/\tau}$$

I_{max}: U/R [A]
t : Switch off time [s]
e : Euler's number: 2,718

The negative sign should be remembered for the decay of the coil voltage U_L after switch-off:

$$u_L = -U \cdot e^{-t/\tau}$$

U: Maximum coil voltage [V]

Familiarity with the response of the coil to sudden changes in voltage, is important for understanding more complex circuits. The following relationships exist between current, voltage and reactance X_L of the coil: Immediately after switching on a voltage, there is only a minimum flow of current whilst the voltage across the coil reaches its maximum value. Thus, according to Ohm's law, X_L is very large. The coil blocks the flow of current. Towards the end of the build-up of the field, at almost maximum coil current I_L and a small residual voltage U_L, X_L has fallen to a very small value and is still reducing towards zero. From this description, it can be recognized the current and voltage at the coil (as seen previously for a capacitor), are out of phase.

- **Reaction of a Coil to Square-wave Voltages**

A square-wave voltage can be considered as a DC voltage, periodically switched on and off. If the pulse duration t_i is at least equal to 5·τ, then the current through the coil and thus the voltage at the resistor, can increase to their maximum values, following an e-function. In the interpoles period (if tp ≥ 5·τ), the current in the coil I_L and voltage U_R again, fall to zero (I_L/U_R in Fig. 11.3.2.1 right).

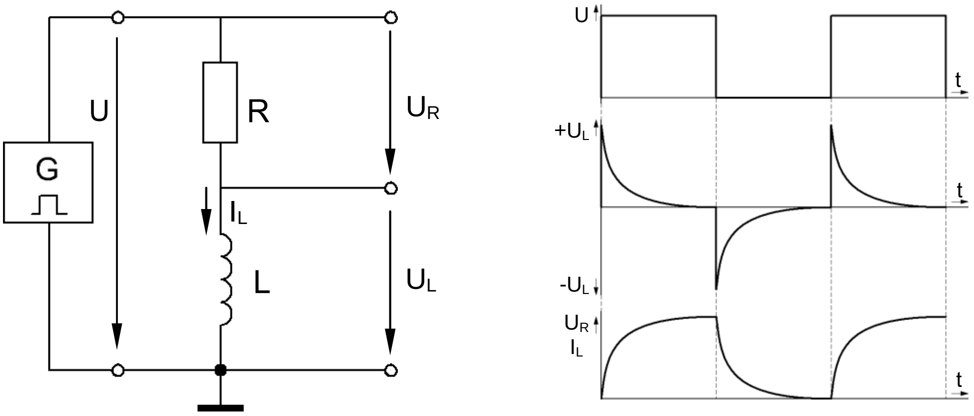


Fig. 11.3.2.1: Reaction of a coil to a square-wave voltage

The voltage drop across a coil, is given by $U_L = U - U_R$ in the form of needle pulses. The shorter the time constant $\tau = L / R$, the narrower are the needle pulses. The negative needle pulses in the inter pulse period, are the result of the opposing self- induced voltage that attempts to maintain the flow of current in the coil.

The response of a coil will now be examined using the components shown, together with the input voltage given in Fig. 11.3.2.2.

- Assemble the circuit in Fig. 11.3.2.2 on the Electronic Circuits Board.
- Set the square-wave generator to a peak voltage of U_p = 5 V at a frequency of f = 800 Hz.
- Connect the oscilloscope as shown in Fig. 11.3.2.2. Adjust the oscilloscopeso that both signals are displayed, one above the other with at least one complete period of the signal.

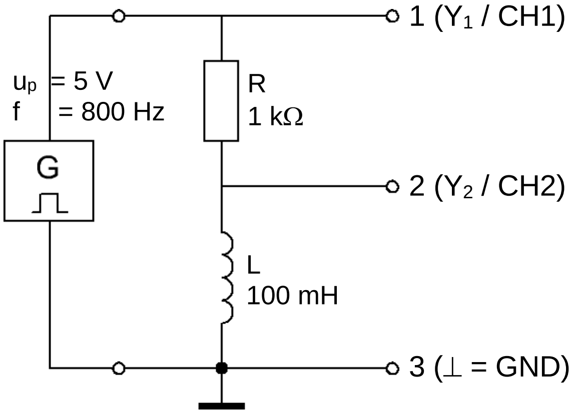
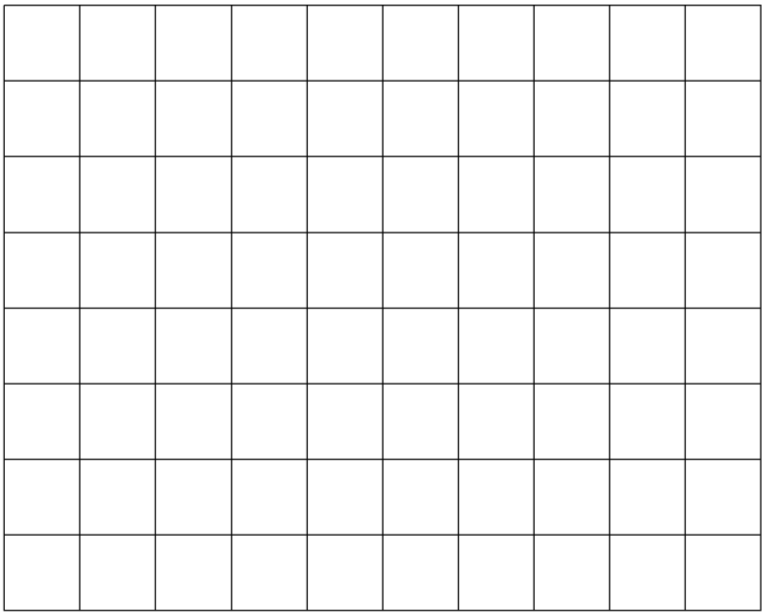


Fig. 11.3.2.2: Square-wave voltage in an LC-circuit

- Draw the signals displayed of U and U_L in the chart in Fig. 11.3.2.3.

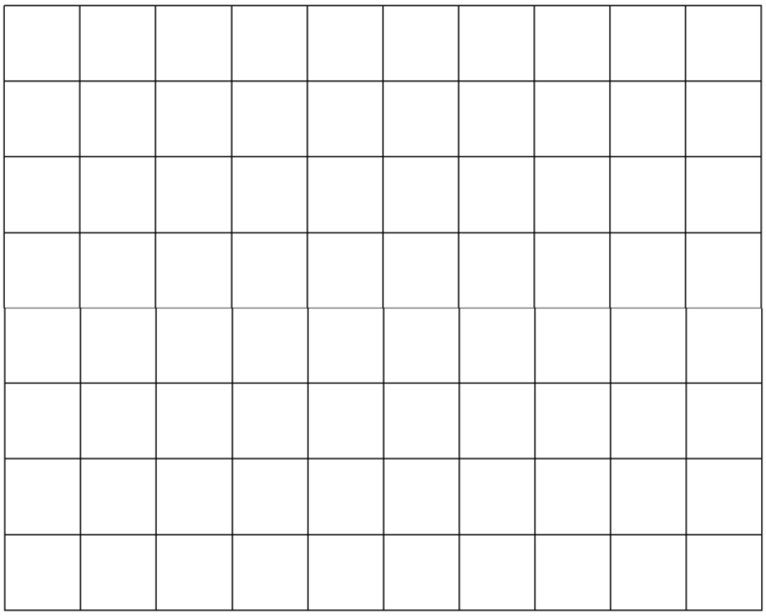
Fig. 11.3.2.3: Display, U and U_L

Oscilloscope settings:
X : 0,2 ms/ div.
Y_1 : 5 V/ div., DC
Y_2 : 2 V/ div., DC



- Exchange R and L in the circuit, to display the signal across resistor R.
- Draw the signals displayed of U and U_R (→ I_L) in the chart in Fig. 11.3.2.4.

Fig. 11.3.2.4:
Display, U and U_R ($\rightarrow I_L$)



Oscilloscope settings:
X : 0,2 ms/ div.
Y_1 : 2 V/ div., DC
Y_2 : 2 V/ div., DC

- From the waveforms drawn, determine the time constant τ as accurately as possible. Check your result by calculation.

  τ From waveforms:

  τ By calculation:

- What is the value of current in the coil (I_L), 0,2 ms after the start of the pulse t_i? Determine the value of U_R, by Ohm's law, using the values drawn or read from the oscilloscope a screen. Check your measurement by calculation (use the equation from section 10.3.1).

  u_R Measured after 0,2 ms / read from screen:

  i_L by calculation:

- Explain the deviation between your calculated value and the measured value of u_R?

- Calculate the inductance L from the value measured for τ.

- What voltage can be measured across the coil, 0,2 ms after the start of the inter pulse period t_p? Read the value as accurately as possible, from the oscilloscope screen. Optimize the oscilloscope settings for reading the value accurately.

  U_L = ...

- Check the value read, by calculation.

- At what time has the magnetic field of the coil, reached its full strength?

- In the circuit of Fig. 11.3.2.2, the resistor is replaced by one of R = 220 Ω. What effect has this change to the circuit have, on the time constant and the build-up of the field?

- Check your statement by measurement. Replace the resistor in the circuit of Fig 11.3.2.2 with one of R = 220 Ω. Display the voltages across the components on the oscilloscope. Compare the voltage waveforms with the results of the measurements in Figs. 11.3.2.3/4).

12.4 Inductance with a Sine-wave Voltage

Phase Shift between Current and Voltage

It has already been seen that with a square-wave voltage, voltage and current at a coil were out of phase. Due to the self-induction, the voltage immediately increases to a maximum, whilst the current increases only after the self-induced voltage has decayed: the current lags the voltage.

With a sine-wave voltage applied, the polarity of the magnetic field reverses, in rhythm with the frequency of the current through the coil (I_L in Fig. 11.4.1.1). The voltage across the coil leads on this process by a quarter-period (U_L in Fig. 11.4.1.1): The voltage is at a maximum when the current cuts the zero axis. Thus, between voltage and current, there is a phase shift of 90°.

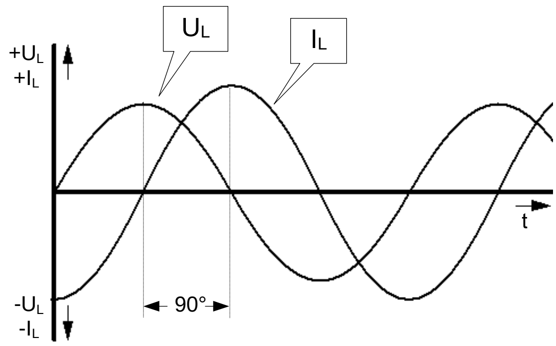
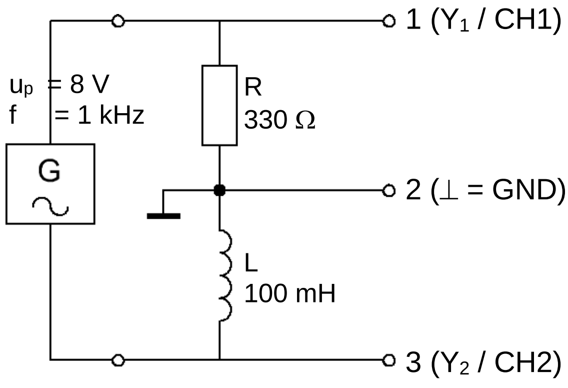


Fig. 11.4.1.1: Phase shift between voltage and current at a coil

The phase shift between current and voltage will now be proved in a circuit as shown in Fig. 11.4.1.2.

- Assemble the circuit in Fig. 11.4.1.2 on the Electronic Circuits Board.

Fig. 11.4.1.2: Exercise circuit to show the phase shift between U and I



Since the changes of current and voltage at an ohmic resistor are always proportional to each other, U_R (Y_1 / CH1) can be used for showing the phase of the current I_L in the circuit.

- Set the signal generator to a sine-wave voltage $u_{pp} = 16$ V at a frequency of f = 1 kHz.

- Connect the 2-channel oscilloscope as shown in Fig. 10.4.1.2.

By adjusting the 0-axis (GND) between R and L, the voltages U_R and U_L can both be displayed on the 2-channel oscilloscope. However, the negative voltage U_L (Y_2 / CH2) has a 180° phase shift. For measuring the correct phase relationship, one channel of the oscilloscope must be operated in the 'inverted' mode.

- Display the voltage waveforms U_R and U_L on the oscilloscope. Adjust the oscilloscope for a display of least 2 periods of the sine-wave.

- Draw the signal waveforms displayed in the chart, Fig 11.4.1.3.

Oscilloscope settings:
X : 0,2 ms/ div.
Y_1 : 2 V/ div., AC
Y_2 : 2 V/ div., AC, inverted

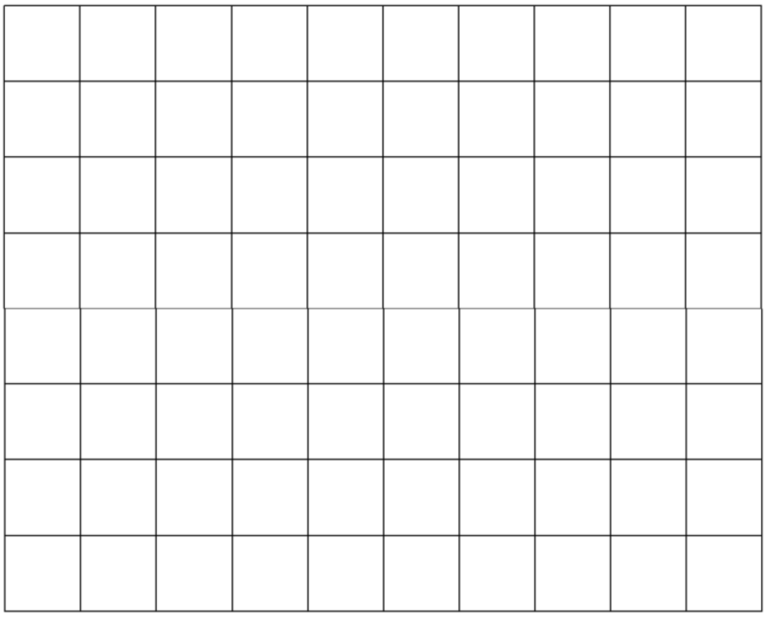


Fig. 11.4.1.3: Phase shift between voltage and current at the coil

- From the waveforms, determine the periodic time T, the frequency f and the angle of phase shift φ between voltage and current.

- In the circuit of Fig. 11.4.1.2, the resistance of 330 Ω in increased to 1 kΩ. What effects do you expect to see on the signals displayed on the oscilloscope? What is the tendency of events and check your considerations by measurement?

Inductive Reactance, X_L

On an inductance, a sinusoidal voltage generates a magnetic field that periodically reverses in polarity. The coil presents a limiting resistance to the current produced that lags on the voltage by 90°. At this resistance, there is no thermal (active) powerdissipated, therefore the resistance is known as '**inductive reactance, X_L**'.

The magnitude of the inductive reactance X_L is proportional to the inductance L of the coil and the frequency f of the applied sinusoidal voltage:

$$X_L = 2 \cdot \pi \cdot f \cdot L$$

L: [H]
f : [1/s]
X_L: [Ω]

With a given coil current I_L and a known coil voltage U_L, Ohm's law can be used for calculating the value of X_L:

$$X_L = \frac{U_L}{I_L}$$

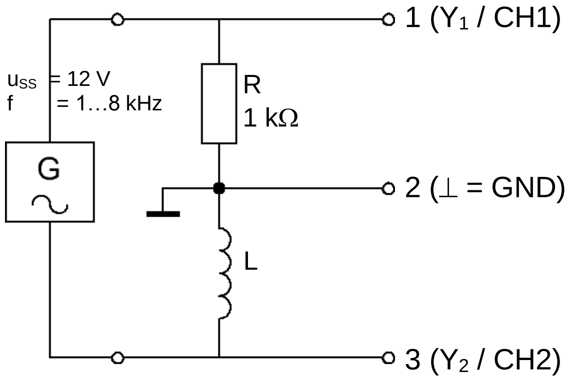
U_L: [V]
I_L: [A]
X_L: [Ω]

The response of inductive reactance X_L will now be examined using the circuit in Fig. 11.4.2.1, assembled on the Electronic Circuits Board. The current flow through the inductance will be calculated from the voltage drop U_R across the resistor R = 1 kΩ (U_R and I_L in-phase).

By adjusting the 0-axis (GND) between R and L, the voltages U_R and U_L can both be displayed on the 2-channel oscilloscope.

- Assemble the circuit in Fig. 11.4.2.1 with L = 100 mH on the Electronic Circuits Board (assembly layoutnotes and the measurement details, are given at the end of this section).
- Set the signal generator to a sine-wave voltage u_{pp} = 12 V at an initial frequency of f = 1 kHz.
- Connect the 2-channel oscilloscopeas shown in Fig. 11.4.2.1.

Fig. 11.4.2.1: Exercise circuit to examine the relationship between X_L, f and L



- Measure the peak-to-peak values of the voltages U_L and U_R at the frequencies given in the table 11.4.2.2. Complete these measurements with 2 different coils:

  Coil 1: L = 100 mH (component in plastic housing)
- Enter the values measured in the table.

Table 11.4.2.2: Reactance X_L, inductance L and frequency f

f [kHz]		**1**	**2**	**3**	**4**	**6**
U_L [V_{pp}]	**100 mH**					
U_R[V_{pp}]	**100 mH**					
I_L[mA_{pp}]	**100 mH**					
X_L[kΩ]	**100 mH**					

- Calculate the peak-to-peak values of current I_L and enter the values in the table.
- Calculate the values for X_L and complete the table with your results.
- Plot the calculated values for the reactance X_L in the chart (Fig. 11.4.2.3).

- Draw the characteristic $X_L = f(f)$ for both coils.

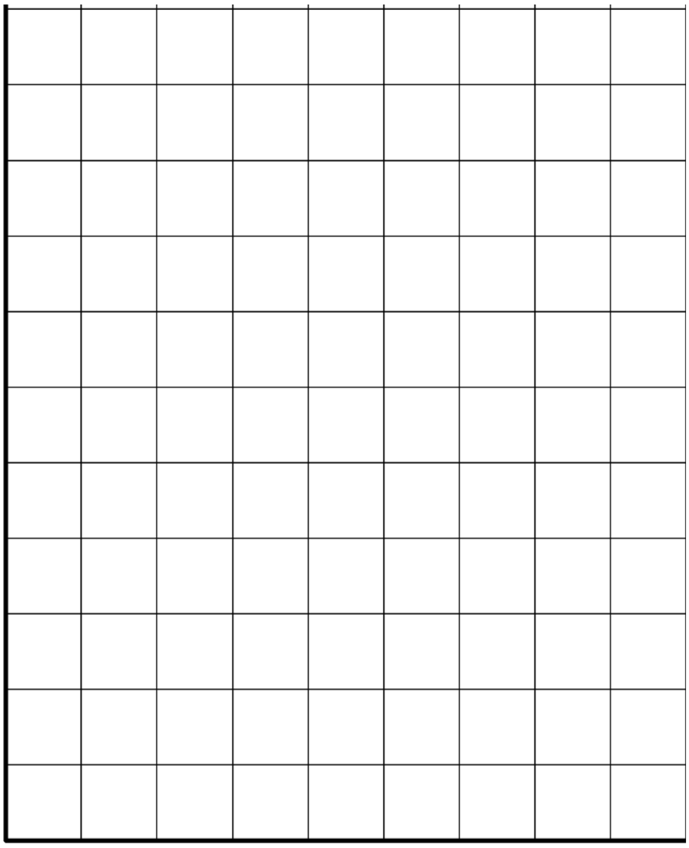


Fig. 11.4.2.3:
Characteristic $X_L = f(f)$

- Check the measured values by calculation at $X_L = f$ (6 kHz) for the coil L = 100 mH.

- Check the nominal value of the coil L = 100 mH by calculation. Use the values measured at 4 kHz.

- Explain the deviation between the two check calculations?

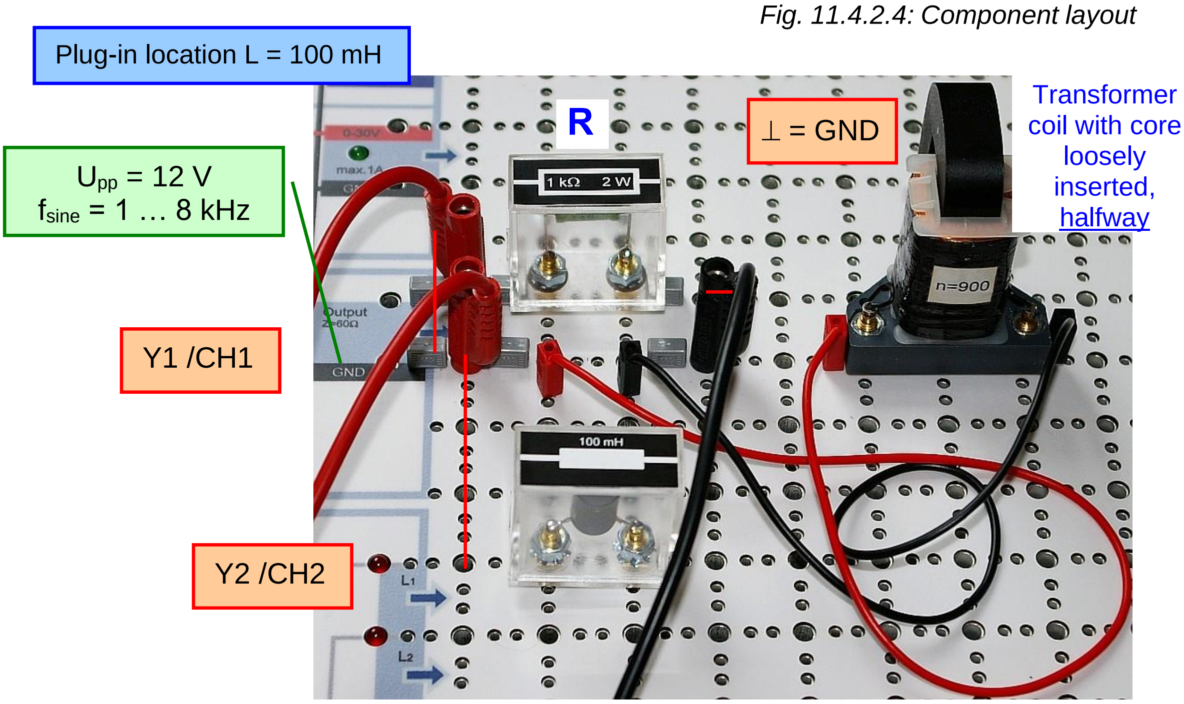
- What rules or relationships can be deduced from the shape of the characteristics?

- What tendency does the reactance X_L of a coil L = 0,01 H (= 10 mH), show at very high (> 10 MHz) and very low (< 100 Hz) frequencies?

Exercise assembly for examining the relationships between reactance X_L, inductance and frequency.

Fig. 11.4.2.4 shows one possible layout of the components on the Electronic Circuits Board. In the layout, the coil L = 100 mH, after completing the measurements, has been removed from its original position and inserted somewhere else withoutconnections. The transformer coil is then inserted in the circuit by completing its connections.

Fig. 11.4.2.4: Component layout



- **Active and Reactive Power in a Coil**

An *ideal coil* does not dissipate any **active power**. Although the build-up of the magnetic field requires energy, the coil stores the field energy and later when the field decays, the stored energy is again available. So, in this respect, voltage and current inan inductance produce only **reactive power**.

In *real coils* however, *ohmic losses* are present, such as:
- Losses in the windings
- Current displacement losses in the windings
- Eddy current losses in the core of the coil
- Losses due to magnetic reversal in the core of the coil
- Eddy current losses in the windings
- Scattering (or leakage) losses.

Losses in the windings are independent of frequency and are caused by the ohmic resistance of the wire used for the windings. The losses can be in the region of a few hundred ohms when the coil consists of many turns of thin wire (the inductance L, increases with the square of the number of windings N).

Current displacement losses increase with the frequency of the AC current, that is forced from inside the wire to the surface area, or skin of the wire. This reduces the effective cross-sectional area of the wire, causing the wire resistance to increase. This effect is called the **skin-effect**.

Eddy current losses are produced in the core of the coil and in the windings, by induced voltages. They cause irregular current patterns that produce warmth in the material. These losses increase with the square of the frequency.

Losses due to magnetic reversal in the core of the coil are frequency-dependent and correspond to the power that must be used to align the molecular magnetic particles in the core material.

Scattering (or leakage) losses increase with frequency. They occur when part of the magnetic field of the coil induces eddy currents in metal objects in the vicinity of the coil.

The active power losses are combined and represented by the **power loss resistance R_v** imagined to be connected in series with the inductance (Fig. 11.4.3.1). The loss current produces the voltage drop U_{Rv} across R_v. Since the voltage at the coil (U_L) leads the loss current and thus, the voltage U_{Rv} by 90°, the relevant vectors show a loss angle, δ (Fig. 11.4.3.1).

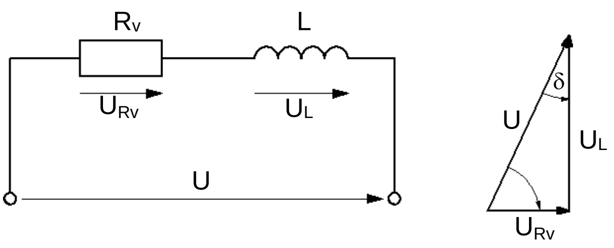


Fig. 11.4.3.1: Losses at a real coil

The active powerlosses give the **lossfactor, d:**

$$d = \tan\delta = \frac{R_V}{X_L} = \frac{U_{Rv}}{U_L}$$

d: Loss factor, [no dimensions]
δ: Loss angle [°]
X_L: Reactance [Ω]
R_v: Loss resistance [Ω]

The **active power (P)** consumed by a coil is the result of unwanted but unavoidable losses. They must be accepted within reason, due to the physical limits in the manufacture of coils.

The **reactive power Q** at a coil is given by the product of coil voltage and reactive current. It can be represented as a multiplication of the instantaneous values of u_L and i_L in a line chart with the phase relationships (Fig. 11.4.3.2).

The reactive power Q_L is calculated from:

$$Q_L = U_L \cdot I_L \quad \text{or}$$

$$Q_L = \frac{U_L^2}{X_L} \quad \text{or}$$

$$Q_L = I_L^2 \cdot X_L$$

Q_L: Reactive power, [W]
U_L: [V]
I_L: [A]
X_L: [Ω]

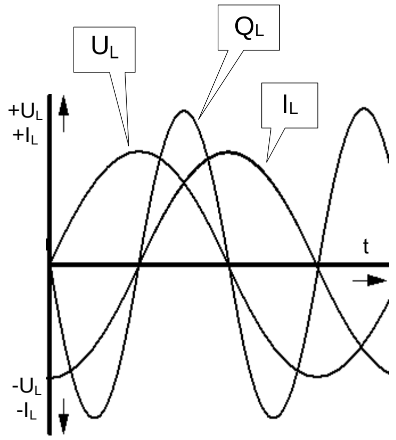


Fig. 11.4.3.2: Reactive power, Q_L

In an example circuit, the response of current and voltage will be displayed on an oscilloscope, for one complete period of a sinusoidal voltage. The waveforms displayed will then be drawn in a chart. Finally, the waveform of the reactive power curve will be plotted from the values measured and the curve drawn in the chart.

- Assemble the circuit in Fig. 11.4.3.3 on the Electronic Circuits Board.

The current I_L is determined indirectly from the voltage U_R measured on Y_1 / CH1 of the oscilloscope. Because the earth point (GND) is taken between R and L in the circuit, one channel of the oscilloscope must be operated in the 'inverted' mode to display the correct phase relationship.

- Set the signal generator to a sine-wave voltage $u_p = 6$ V at a frequency of f = 1 kHz.
- Connect the 2-channel oscilloscope as shown in Fig. 11.4.3.3.
- Display the voltage waveforms U_R and U_L on the oscilloscope.

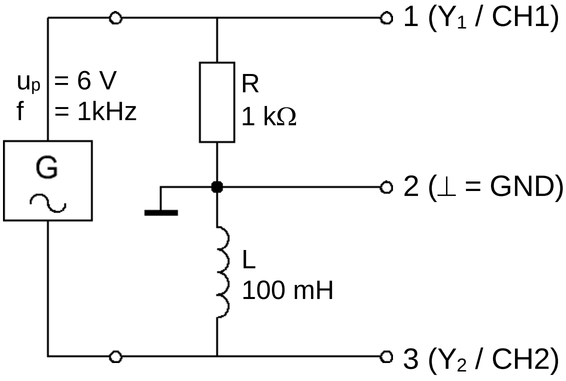


Fig. 11.4.3.3: Exercise circuit for measuring the inductive reactance, Q_L

- Measure the instantaneous values of the voltages u_R and u_L at the times given in table 11.4.3.4. Enter the values in the table.
- Calculate the instantaneous values of current in the coil i_L from u_R and enter the values in the table.

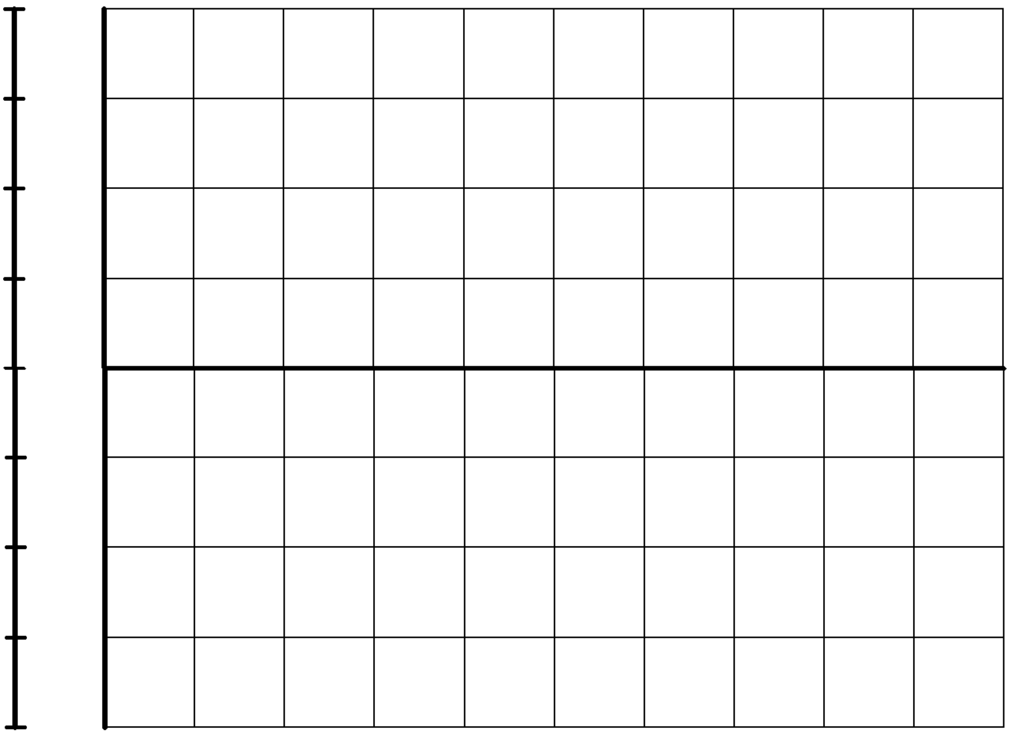
- Calculate the reactive power q_L from u_L and i_L at the times given in table. Complete the table with your results of calculation.

Table 11.4.3.4: Instantaneous values, exercise circuit in Fig. 11.4.3.3

t [ms]	**0**	**0,1**	**0,2**	**0,25**	**0,4**	**0,5**	**0,6**	**0,75**	**0,8**	**0,9**	**1**
$\mathbf{u_R}$ [V]											
$\mathbf{u_L}$ [V]											
$\mathbf{i_L}$ [mA]											
$\mathbf{q_L}$ [mW]											

- Sketch the voltage curve $U_L = f(t)$, the current curve $I_L = f(t)$ and the power curve $Q_L = f(t)$ as accurately as possible, in the chart given in Fig. 11.4.3.5.

Fig. 11.4.3.5: Waveforms of voltage U_L, reactive current I_L and reactive power Q_L at the coil



Experiment 12

13. Circuiting of Resistor, Capacitor and Coil

13.1 Series Circuiting of Resistor, Capacitor and Coil

General Information

When connecting a sinusoidal AC voltage to a series circuit of resistor, capacitor and coil, the same currentflows through all three components. The voltage U_R isphase equal with the current I. The voltages U_R, U_C, U_L and U are phase-shifted. The resistances behave in accordance with the voltages.

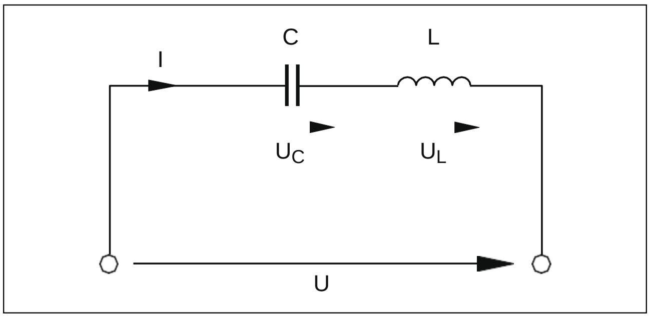


Fig. 12.1.1

Pointer diagram voltages ($U_C > U_L$)

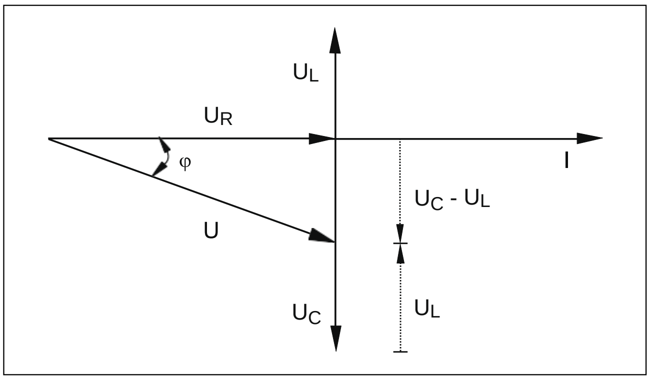


Fig. 12.1.2

Pointer diagram resistances ($X_C > X_L$)

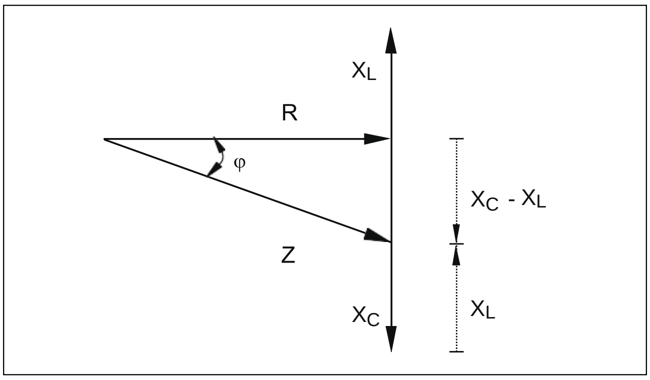


Fig. 12.1.3

U_R = active voltage in V

U_L = reactive voltage (inductive), coil voltage in V U_C = reactive voltage (capacitive), capacitor voltage in V

U = phase voltage, total voltage in VI = current in A

φ = phase angle in ° (degrees)

The pointer diagrams show the case in which the voltage U_C or the resistance X_C is greater than the voltage U_L or the resistance X_L respectively, i. e. the capacitive part is superior.

X_L = inductive reactance, coil resistance in Ω

X_C = capacitive reactance, capacitor resistance in Ω

R = active resistance in Ω

Z = apparent resistance in Ω

The voltage U follows the active voltage U_R. If the inductive part is superior ($U_L > U_C$) the relation-ships are accordingly reversed. If the inductive and capacitive parts are equal, they equalize each other due to the phase shift of 180°; inthis case the voltage U is equal to the active voltage U_R and the apparent resistance Z is equal to the active resistance R.

Below are some formulae for calculating values in a series circuit of resistor, coil and capacitor.

Apparent voltage U

$$U = \sqrt{U_R^2 + (U_L - U_C)^2}$$

$$U = Z \cdot I$$

Apparent resistance Z

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$Z = U/I$$

Tan of the phase angle φ

$$\tan\varphi = \frac{U_L - U_C}{U_R} = \frac{X_L - X_C}{R}$$

Experiment Section

Measure the voltages U_R, U_C and U_L in a series circuit of resistor, capacitor and coil, determine whether the total voltage U precedes or follows the voltage U_R and measure the phase angle φ with the oscilloscope.

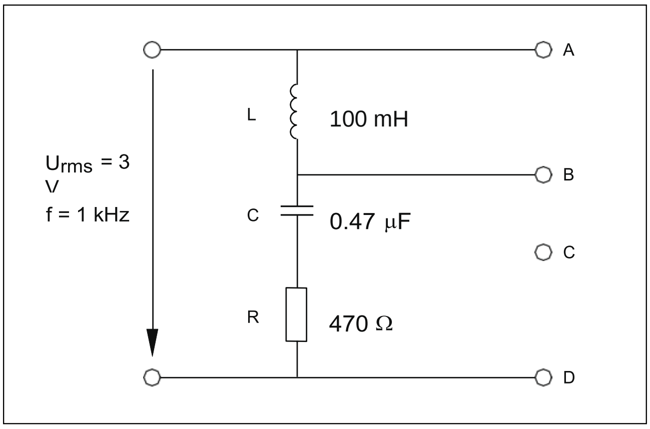


Fig. 12.1.1

Experiment procedure

- Set up the experiment according to the circuit (Fig. 12.1.1), connect the function generator and setthe following voltage:

U_{rms} = 3 V (sinusoidal); f = 1 kHz

- Measuring with the multimeter

Coil voltage U_L
(Test points A - B)

U_L =

Capacitor voltage U_C
(Test points B - C)

U_C =

Active voltage U_R
(Test points C - D)

U_R =

- Determination of phase relation of U to U_R:

- Connect the oscilloscope as follows to determine the phase angle φ between the total voltage U andthe active voltage U_R:

Test point C to channel 1 (Y_1) Test point A to channel 2 (Y_2) Test point D to ground

- Make the other settings on the oscilloscope according to the specifications below the grid (Fig.12.1.2).

- Draw the displayed voltage curves in the grid (fig.12.1.2) and determine the phase angle φ.

Period duration T

T =

Phase angle φ

φ =

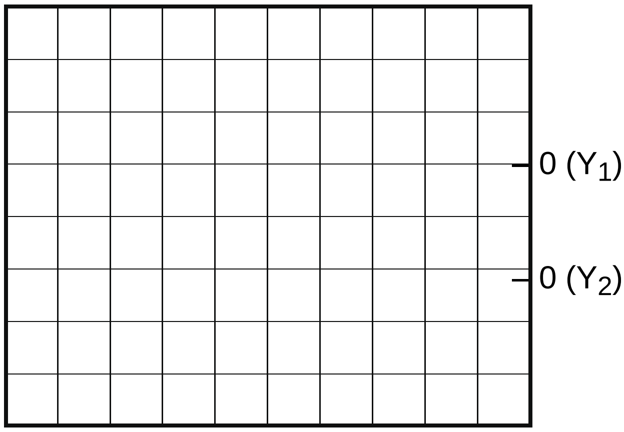


Fig. 12.1.2

Settings:

X = 0.1 ms /

div. Y_1 = 2 V /

div.

Y_2 = 2 V / div.

Triggering: Y_1

Remarks:

Y_1: active voltage U_R

Y_2: total voltage, apparent voltage U

12.2 Parallel Circuiting of Resistor, Capacitor and Coil

General Information

If a sinusoidal AC voltage is connected to a parallel circuit of resistor, capacitor and coil the voltage on all components is the same.

The total current I is divided into active current I_R, capacitor current I_C and coil current I_L. A phase shift occurs between the currents I_L, I_C, I_R and I due to the reactance X_L of the coil and X_C of the capacitor (see pointer diagram 12.2.1). The current I_C precedes current I_R constantly by 90°, whilst the current I_L follows the active current I_R constantly by 90°. Currents I_C and I_L are therefore in opposite phase (180°) and equalize each other wholly or partly depending on their size.

When $I_C = I_L$ the two currents equalize each other, the total current I is equal to the active current in phase and value (resonance).

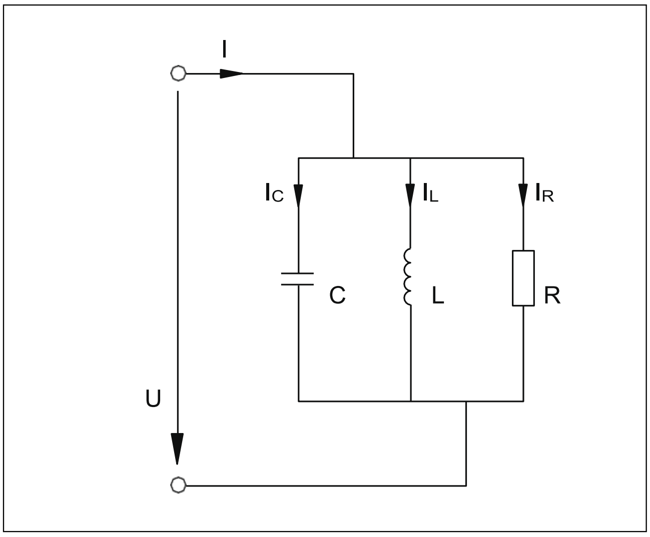
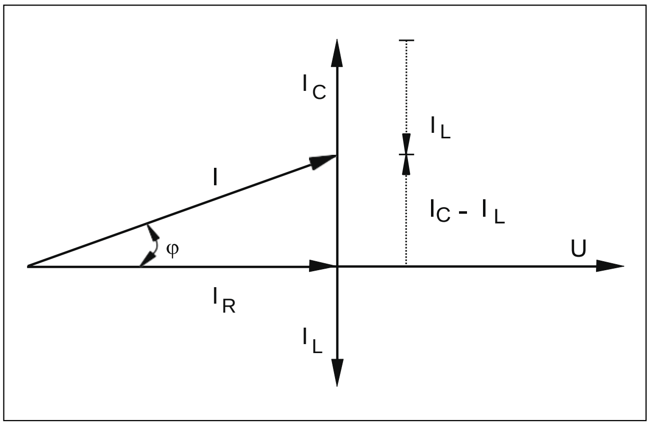


Fig. 12.2.1

Pointer diagram for currents ($I_C > I_L$)



I = total current, apparent current in A

I_C = reactive current (capacitive), capacitor current in A

I_L = reactive current (inductive), coil current in A

I_R = active current in A

U = voltage in V

φ = phase angle in ° (degrees)

When $I_C > I_L$ a capacitive residual current is left over, the total current I precedes the active current I_R.

When $I_C < I_L$ an inductive residual current is left over, the total current I follows the active current I_R.

The pointer diagram 12.2.2 shows how the conductance's B_L, B_C, G and Y behave in a parallel circuit of resistor, capacitor and coil.

Pointer diagram for conductance's

($B_C > B_L$)

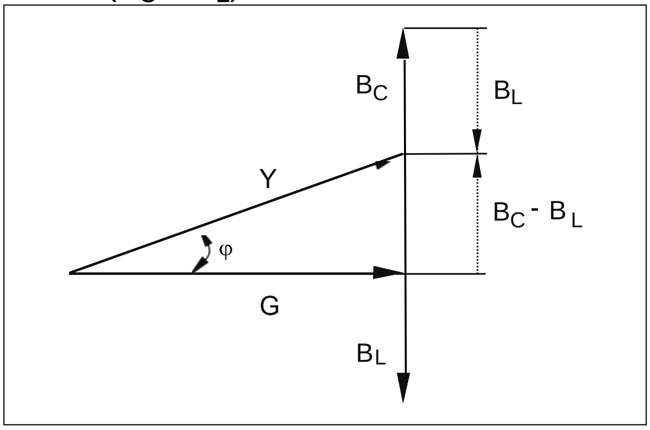


Fig. 12.2.2

B_C = reactive conductance (capacitive) in S B_L = reactive conductance (inductive) in S Y = apparent conductance in S

G= active conductance in S

The pointer diagrams are prepared for the case $I_C > I_L$ or $B_C > B_L$.

Formulae for calculating the values in a parallel circuit of R, L and C:

Apparent current I

$$I = \sqrt{I_R^2 + (I_C - I_L)^2}$$

Apparent conductance Y

$$Y = \sqrt{G^2 + (B_C - B_L)^2}$$

Tan of the phase angle φ

$$\tan \varphi = \frac{I_C - I_L}{I_R}$$

$$\tan \varphi = \frac{B_C - B_L}{G}$$

12.2.1 Experiment Section

Experiment

Measure the current I, I_L, I_C and I_R in a parallel circuitof resistor, capacitor and calculate the phase angle. Then construct the pointer diagrams for currents and conductance's.

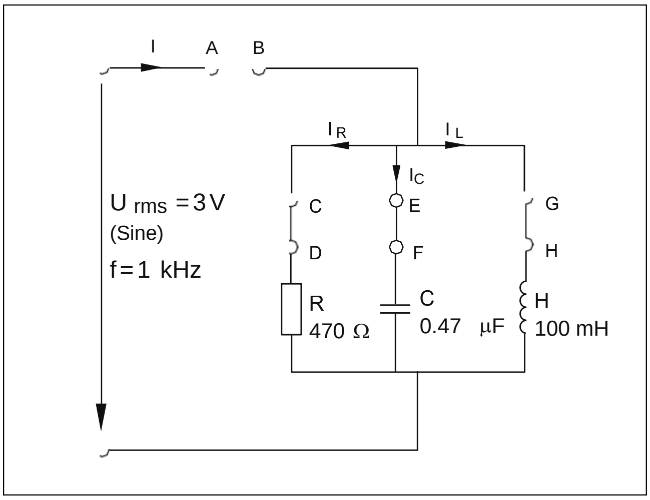


Fig. 12.2.1.1

Experiment procedure

- Set up the experiment according to the circuit

(Fig. 12.2.1.1), connect the function generator and setthe following voltage:

U_{rms} = 3 V (sinusoidal); f = 1 kHz

Measuring with the multimeter:

Total current I

(Test points A - B)

I =

Phase angle φ

$$\tan \varphi = \frac{I_C - I_L}{I_R} =$$

Active current I_R

(Test points C - D)

I_R =

Capacitor current I_C

(Test points E- F)

I_C =

Coil current I_L

(Test points G - H)

I_L =

Calculations for constructing the pointer diagrams:

Reactive conductance (capacitive) B_C

$B_C = \omega \cdot C =$

Active conductance G

$G = \frac{1}{R} =$

Reactive conductance (inductive) B_L

$B_L = \frac{1}{\omega \cdot L} =$

Apparent conductance Y

$Y = \sqrt{G^2 + (B_C - B_L)^2} =$

Pointer diagram for currents

1 cm ≙ 2 mA

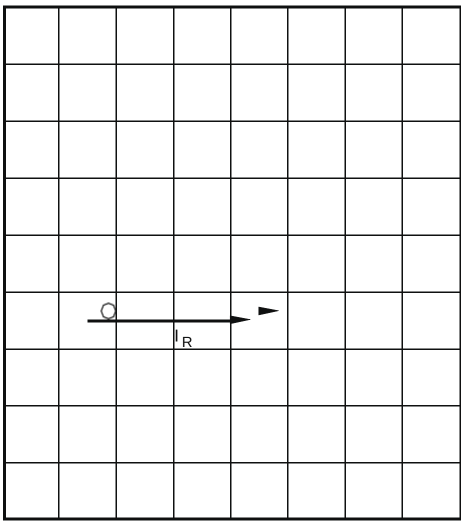


Fig. 12.2.1.2

Pointer diagram for conductance's

1 cm ≙ 1 mS

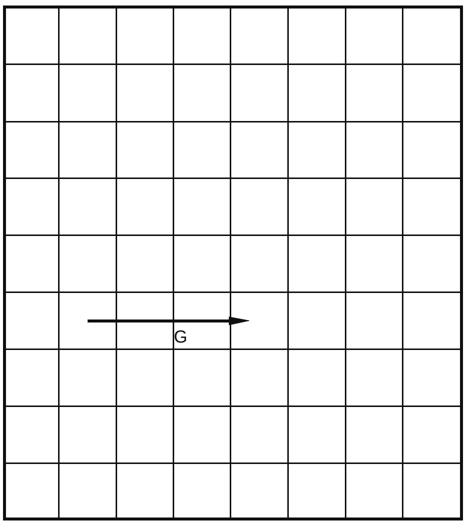


Fig. 12.2.1.3

12.3 Active, Reactive and Apparent Power

General Information

The previous experiments treated exclusively the behavior of voltage, current and resistance connectingcapacitors, coils and ohmic resistors.

The object of the experiment are the resulting powers. Like the voltages and currents the powers are also mutually phase-shifted due to the reactance's.

In Figs. 12.3.2 to 12.3.4 the power ratios in a parallel circuit of resistor, capacitor and coil (fig. 5.10.1.1) are shown as pointer diagrams.

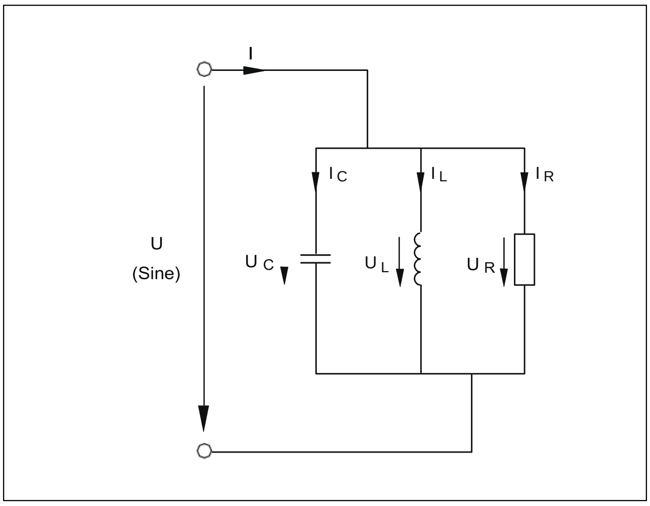


Fig. 12.3.1

Pointer diagram for powers ($Q_C > Q_L$)

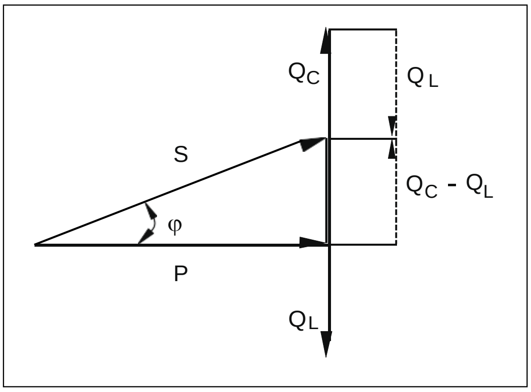


Fig. 12.3.2

Pointer diagram for $Q_L > Q_C$

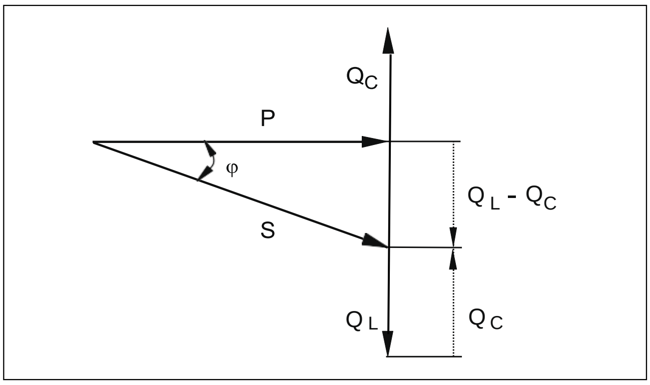


Fig. 12.3.3

S = apparent power

in VAP = active power in W

Q_L = inductive reactive power in

var Q_C = capacitive reactive

power in var

φ = phase angle in °
(degrees)

If the capacitive reactive power Q_C is greater than theinductive reactive power Q_L ($Q_C > Q_L$) the apparent power S precedes the active power P (fig. 5.10.1.2).

In the reverse case ($Q_L > Q$) the apparent power S follows the active power P (fig. 5.10.1.3).

Pointer diagram for
QC = Q_L

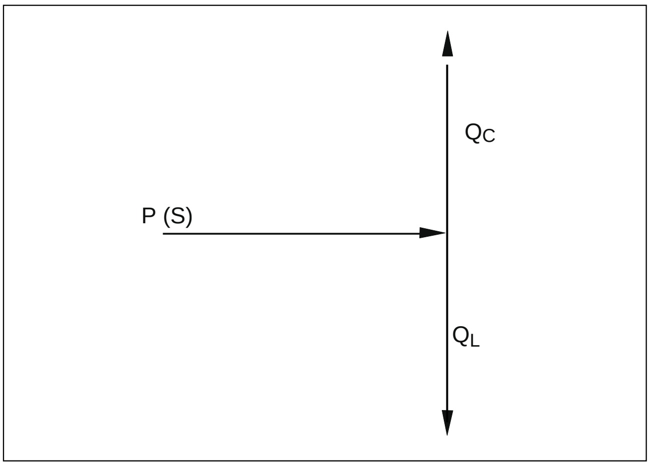


Fig. 12.3.4

If both reactive powers are the same (Q_L = Q_C) theyneutralize each other and the apparent power S is equal to the active power P (fig. 12.3.4).

The representation of the power ratios in a series circuit of resistor, capacitor and coil are similar to thosein a parallel circuit except that the power pointers $Q_C$and Q_L are reversed.

The individual powers are calculated with the followingformulae:

Apparent power S

$$S = \sqrt{P^2 + (Q_L - Q_C)^2}$$

$$S = U \cdot I$$

Active power P

$$P = U \cdot I \cdot \cos \varphi$$
$$P = S \cdot \cos \varphi$$

Reactive power Q_L, Q_C

$$Q = U \cdot I \cdot \sin \varphi$$

$$\sin = \frac{Q}{S}$$

12.3.1 Experiment Section

Experiment

Measure the apparent power S, the active power P, the reactive powers Q_C and Q_L and calculate the phase angle j in a parallel circuit of resistor, capacitorand coil and then construct the corresponding pointerdiagram.

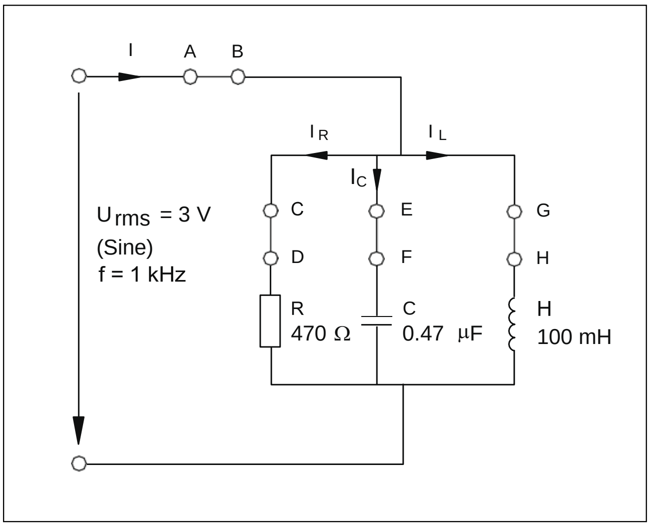


Fig. 12.3.1.1

Experiment procedure

- Set up the experiment according to the circuit (Fig 12.3.1.1), connect the function generator andset the following voltage:

U_{rms} = 3 V (sinusoidal); f = 1 kHz

- Measure the individual currents with the multimeter in order to calculate the powers.

Total current I

(Test points A - B)

I =

Active current I_R

(Test points C - D)

I_R =

Capacitor current I_C

(Test points E - F)

I_C =

coil current I_L

(Test points G - H)

I_L =

Calculate the powers and the phase angle with the given formulae and then draw the pointer diagram.

Active power P

$P = U \cdot I_R =$

Reactive power (capacitive)

$Q_C = U \cdot I_C =$

Reactive power (inductive)

$Q_L = U \cdot I_L =$

Apparent power S

$S = U \cdot I =$

Phase angle φ

$\cos \varphi = \frac{P}{S} =$

Pointer diagram for power

1 cm ≙ 6 mW (mvar, mVA)

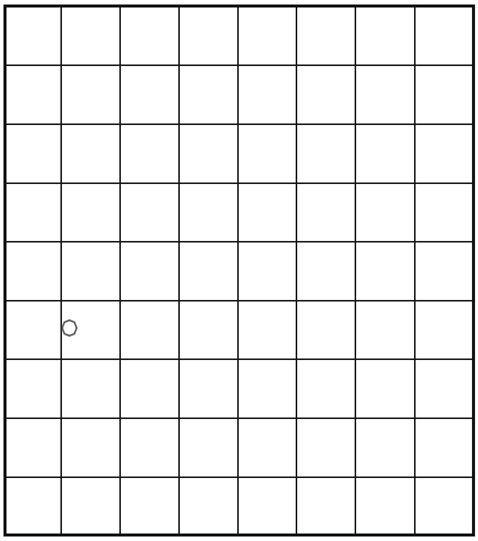


Fig. 12.3.1.2