Constructor University Bremen

Natural Science Laboratory
Electrical Engineering Module I

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Lab Experiment 2 – Ohm’s law

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Place of execution	: Teaching Lab 53
Date of execution	: Oct.17 , 2024

1 Introduction

Ohm's Law is a fundamental principle in electrical engineering that describes the intrinsic relationship between voltage (V), current (I), and resistance (R) in an electrical circuit. Formulated in the 1820s by Georg Simon Ohm, the law asserts that the current flowing through a conductor is directly proportional to the voltage applied across it and inversely proportional to the resistance. This relationship is mathematically represented by the equation $V=IR$, where V represents the voltage, I is the current, and R is the resistance. For materials to adhere strictly to Ohm's Law, their resistance must remain constant despite fluctuations in voltage and current, necessitating stable external conditions, particularly temperature.

Materials that consistently demonstrate this linear relationship are classified as ohmic conductors, characterized by their predictable behavior under varying electrical conditions. Examples include metals like copper and aluminum, which are widely utilized in electrical wiring due to their high conductivity and cost-effectiveness. In contrast, non-ohmic materials, such as semiconductors and certain metal oxides, do not maintain a constant resistance, leading to non-linear current-voltage characteristics. This deviation can result from physical or chemical changes within the material, making it essential to understand the specific properties of each component used in practical applications.

This research aims to systematically investigate the behavior of various resistive components under controlled conditions to assess their compliance with Ohm's Law. Specifically, we will explore the characteristics of copper wire, metal film resistors, and thermistors, including both Positive Temperature Coefficient (PTC) and Negative Temperature Coefficient (NTC) thermistors. The investigation will focus on how these components respond to variations in voltage and temperature, allowing us to differentiate between ohmic and non-ohmic behavior.

The objectives of this experiment are multi-faceted. First, we aim to verify Ohm’s Law across different resistive components by analyzing their current-voltage characteristics. This verification will provide insight into the linearity of their behavior and the impact of external factors on their resistance. Second, we will employ the four-wire (Kelvin) method to accurately measure the resistance of a 1-meter copper wire with a cross-sectional area of 0.25 mm^2. This technique minimizes errors caused by contact resistance and inherent wire resistance, ensuring precise resistance measurements, especially critical when dealing with low-resistance conductors.

Additionally, we will analyze the behavior of metal film resistors, which are known for their stability and precision. Unlike standard wires, these resistors possess defined resistance values that remain relatively unaffected by temperature fluctuations, making them ideal for applications requiring consistent performance. By observing their response to different voltage and current conditions, we will gain a deeper understanding of their operational characteristics.

Finally, we will investigate the temperature-dependent resistance changes in PTC and NTC thermistors. PTC resistors exhibit an increase in resistance as temperature rises, while NTC resistors show a decrease in resistance with increasing temperature. Understanding these behaviors is crucial for applications such as temperature sensing and current limiting, where precise control over resistance is necessary for effective circuit design.

Through this comprehensive examination of resistive components, this research aims to enhance our understanding of electrical resistance, its dependence on various factors, and its implications for designing reliable and efficient electronic circuits. By elucidating the distinctions between ohmic and non-ohmic behaviors, we can better apply these principles in real-world applications and advancements in electrical engineering.

2 Execution

2.1 Experimental Setup

Workbench No.5

Used tools and Instruments:

- Copper wire
- TENMA Voltmeter
- Power supply ELABO
- ELABO Amperemeter

2.1.1 Experimental Part 1 – Setup

- **The objective** - The aim of this experiment is to determine the inherent resistance of a 1-meter copper wire with a known cross-sectional area by employing a high-accuracy measurement technique. The Kelvin (4-wire) method is used to minimize the influence of contact and connecting wire resistances, allowing for precise measurements. Using the resistivity value provided by the manufacturer, which can vary depending on the copper's purity, we will specifically measure the resistance of the wire between designated solder points.

  The resistance R of a conductive material like a copper is described by the following formula:

  $$R = \frac{\rho l}{A}$$

  Where:

  $\rho - material's\ resistivity$

  $l\ - length\ of\ the\ wire$

  $A\ - cross - sectional\ Arrea$

  In this relationship, resistance is directly proportional to the wire's length l and inversely proportional to its cross-sectional area A. This means that as the length of the wire increases, resistance rises, while a larger cross-sectional area reduces resistance. Copper's resistivity can vary based on its purity, which accounts for the different values found in practice. For this experiment, the manufacturer-provided resistivity value is 0.0195 Ω mm2/m which will be used in the calculations.

- **Test Circuit**

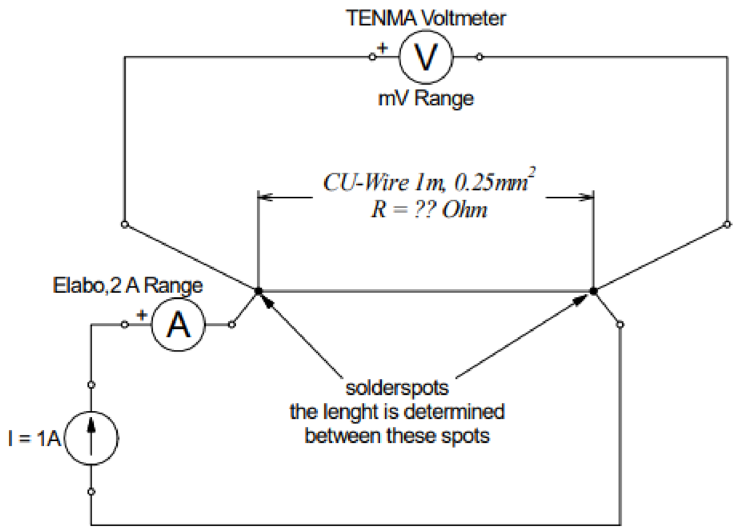


Figure 1. Experimental Setup for the Experiment 1

2.1.2 Experimental Part 1 – Execution and results

Description of the measurement

- A variable power supply was selected from the workbench and adjusted to a voltage of 10 V, configured to operate as a constant current source. The output terminals were then shortened using a lab wire, and the internal instrument was set to current mode, with the current adjusted to approximately 1 A. The prepared copper wire at the workbench served as the test component, and the circuit was assembled, connecting the power supply and instruments through the plugs on the breadboard. After completing the setup, the power supply was switched on, and both the voltage and current were recorded and the experimental resistance was calculated by Ohm's law. A simple circuit was constructed using TENMA Voltmeter, ELABO ammeter, the values that we got from ammeter and multimeter were used to calculate the resistance.

Voltage(V)	Current(A)	Resistance (Ω)
0.0692	1.01E+00	0.068197497

$$R = \frac{Voltage}{Current}$$

Table 1. Calculating the resistance using by Ohm's law

3 Evaluation

3.1 Evaluation Experiment Part 1

- **Calculating the resistance of the wire using the values from the 4-wire measurement**

$$R = \frac{Voltage}{Current} = \frac{V}{I} = \frac{0.0692}{1.0147} = 0.0682\Omega$$

- **Calculating the theoretical resistance of the wire.**

$$R = \frac{\rho l}{A} = \frac{0.0195 * 1}{0.25} = 0.078\Omega$$

- **Calculating the propagation and relative error.**

Propagation Error:

$$E = \left|\frac{\partial R}{\partial V}\Delta V\right| + \left|\frac{\partial R}{\partial I}\Delta I\right| \qquad E = \left|\frac{1}{I} * \Delta V\right| + \left|\frac{-V}{I^2}\Delta I\right|$$

$\Delta V = (0.025\% \; * Value + 5 * resolution) = 0.025\% * 0.0692V + 5 * 0.01mV = 0.0000664078$

$\Delta I = (0.15\% * f.Value + 0.01\% f.Range) = 0.15\% * 1.0147A + 0.01\% * 2A = 0.001722A$

delta V	6.64078E-05
v	0.0692
delta I	0.001722
I	1.0147
delta R	0.000181181

Table 2. Calculating error propagation

According to these formulas the value of the error propagation was received which is: 0.00018 Ω

Relative Error:

$$Relative\ Error = \left(\frac{\Delta V}{V} + \frac{\Delta I}{I}\right) * 100\% = 0.26567\%$$

- **Differences to the theoretical value of the wire resistance**

The experimental resistance value should ideally align closely with the theoretical value; however, several factors can lead to discrepancies. In this instance, the theoretical value is perceived to be incorrect, while the measured value is regarded as more accurate. Changes in resistivity due to temperature may not be accounted for in the theoretical calculation. For instance, the resistivity of copper increases with rising temperature, leading to higher

resistance. If the theoretical value is derived using the resistivity at room temperature, yet the wire experiences heating during the experiment, the calculated value will be lower than the measured one.
In theoretical calculations, ideal conditions are frequently assumed, such as perfect connections. Nevertheless, real experiments often exhibit imperfections, including loose solder joints or connections, which introduce additional contact resistance. This results in an increase in measured resistance compared to the theoretical value. The observed differences arise from the failure to consider factors like temperature effects and contact resistance in theoretical calculations, which are present in the actual experimental setup.

- **Compare the calculated R value from U and I to the value gotten with the multimeter in resistance range. Using the ohm range of the multimeter includes methodical error. Name these errors. How are they avoided using the 4-wire method?**

When an ohmmeter is used to measure resistance, more than just the resistance of the intended wire or component is measured. Contact resistance and test lead resistance are also included in the measurement. This additional resistance results in an increased value for the wire or component being measured. Even small contact or lead resistances can significantly affect the readings in low-resistance measurements, potentially leading to an overestimation of the resistance. The accuracy of measurements in this range is particularly susceptible to errors caused by contact and lead resistances. In such cases, these inaccuracies can substantially contribute to the total resistance recorded. The 4-wire method has been established as an accurate technique for measuring low resistances by addressing errors related to contact and lead resistances. By employing two separate wires—one for supplying voltage and the other for current—this method ensures that the voltage reading is unaffected by the resistance of the wires or connection points. Furthermore, since the voltage wires carry no current, no voltage drop occurs across them, thereby minimizing resistance errors. As a result, the 4-wire method is significantly more precise for low-resistance measurements, ensuring that only the resistance of the desired wire or component is accurately measured.

4 Experiment Part 2

4.1 Experiment Part 2: Resistance of a metal film resistor

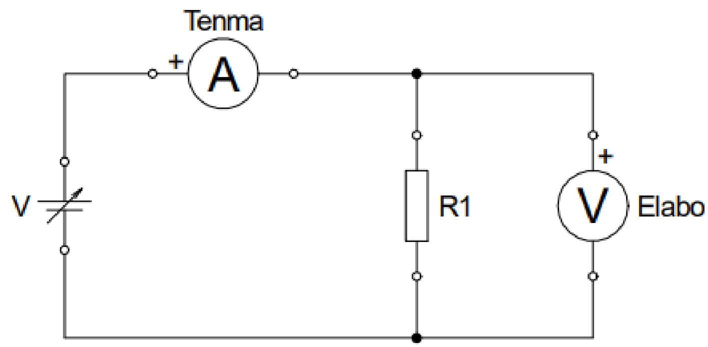
Used tools and instruments:

- Breadboard, Tools box from workbench
- TENMA amperemeter
- Power supply ELABO
- ELABO voltmeter

4.2 Experiment Part 2 – Setup

- **The objective -** The purpose of this experiment is to evaluate the behavior of a metal film resistor when subjected to varying voltage levels. Although metal film resistors are not perfectly ohmic, they are assumed to exhibit a nearly constant resistance within the limited scope of this experiment. The objective is to measure the resistor's resistance at different voltage values to observe its stability and suitability as an ohmic component in circuit applications.

- **Test Circuit**



$$R_1 = 1\text{k}50\,\Omega$$

Figure 2. Experimental Setup for the Experiment 2

4.3 Experiment Part 2 – Execution and result

Description of the measurement:

- In this experiment, the supply voltage is gradually varied from 0 to 24 V in 2 V increments. At each step, both the voltage and the resulting current through the resistor are recorded. These measurements are collected directly into a spreadsheet program to facilitate data organization and analysis. Using this data, a current-voltage diagram is created to visually represent the resistor’s behavior across the range of applied voltages. This setup allows for a clear observation of the resistor's performance as the voltage increases.

V(V)	I(A)	R(Ω)
2.085	1.395	1.494624
4.014	2.688	1.493304
6.054	4.057	1.492236
8.004	5.364	1.49217
10.035	6.725	1.492193
12.033	8.065	1.492002
14.031	9.406	1.491707
15.988	10.719	1.491557
17.992	12.065	1.491256
19.966	13.393	1.490779
21.91	14.723	1.488148
23.92	16.078	1.487747

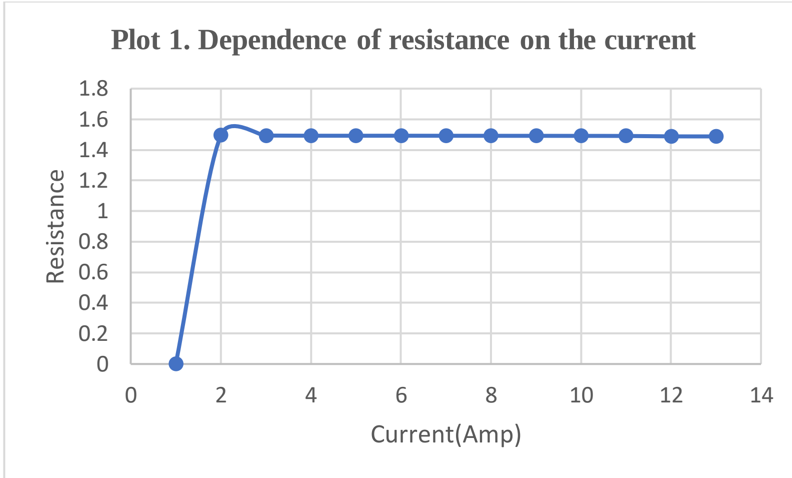
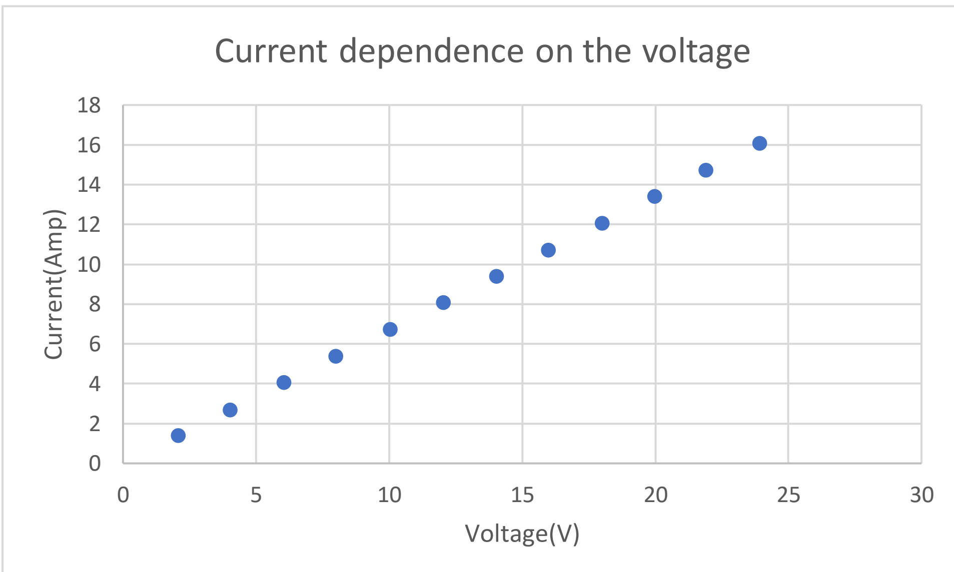


Table 3. Calculating the resistance using by Ohm's law



Plot 2. How the current is depends on the current through the film resistor

As expected, the resistance should remain constant regardless of changes in applied voltage, assuming the resistor possesses a stable, defined resistance. This behavior aligns with the characteristics of an ideal ohmic resistor, where resistance is independent of voltage across a wide range.

5 Experiment Part 3

5.1 Experiment part 3: Resistance of a PTC resistor

Used tools and instruments:

- Breadboard, tools box from workbench
- PTC resistor
- TENMA amperemeter
- Power supply ELABO
- ELABO voltmeter

5.2 Experiment part 3 – Setup

- **The objective -** The objective of this experiment is to investigate the behavior of a Positive Temperature Coefficient (PTC) resistor, specifically a nickel thin-film thermistor, as it undergoes changes in resistance due to temperature variations. The PTC resistor is expected to show an increase in resistance with rising temperature, as described by the formula:

$$R_T = R_{25}(1 + \alpha \Delta T)$$

$R_T - resistance\ at\ temperature\ T$

$R_{25}\ - resistance\ at\ the\ reference\ temperature$

$T - actual\ measured\ temperature$

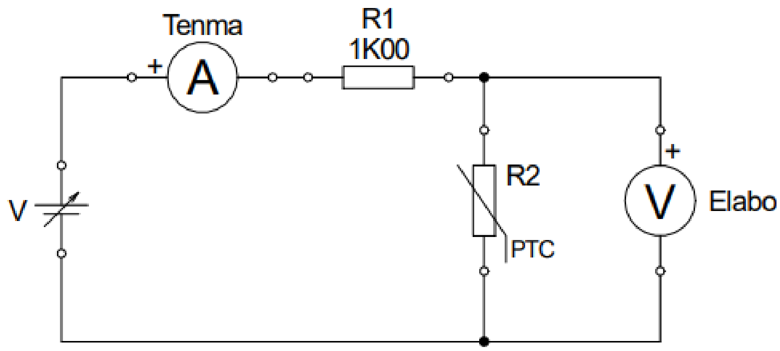
$T_{REF} - reference\ temperature$

$\Delta T\ - temperature\ difference$

$\alpha - temperature\ coefficient\ 3.8724 * 10^{-3} K^{-1}$

This experiment examines how the PTC resistor's resistance responds to self-heating caused by the supplied power, allowing us to observe its temperature-dependent behavior. This analysis provides insight into the suitability of the resistor for applications in environments where temperature fluctuations are expected.

- **Test Circuit**



$$R_2 = 1\text{k}50\,\Omega$$

Figure 3. Experimental Setup for the Experiment 3

5.3 Experiment Part 3 – Execution and result

Description of the measurement:

- The supply voltage was gradually increased from 0 V to 24 V in increments of 2 V. At each voltage step, a waiting period of approximately 2 minutes was observed before recording the voltage and current values. This delay was necessary to allow the component to reach thermal equilibrium after each voltage change, minimizing fluctuations due to self-heating effects. Care was taken not to touch the PTC resistor during measurements to avoid altering its temperature. Voltage and current readings were recorded at each step and used to construct a real-time graph illustrating the relationship between these values.

V(V)	I(A)	R(Ω)
1.236	0.824	1.5
2.443	1.624	1.50431
3.659	2.416	1.514487
4.865	3.185	1.527473
6.067	3.933	1.542588
7.338	4.7	1.561277
8.62	5.44	1.584559
9.895	6.095	1.623462
11.257	6.756	1.666223
12.553	7.42	1.691779
13.954	8.12	1.718473
15.433	8.604	1.793701

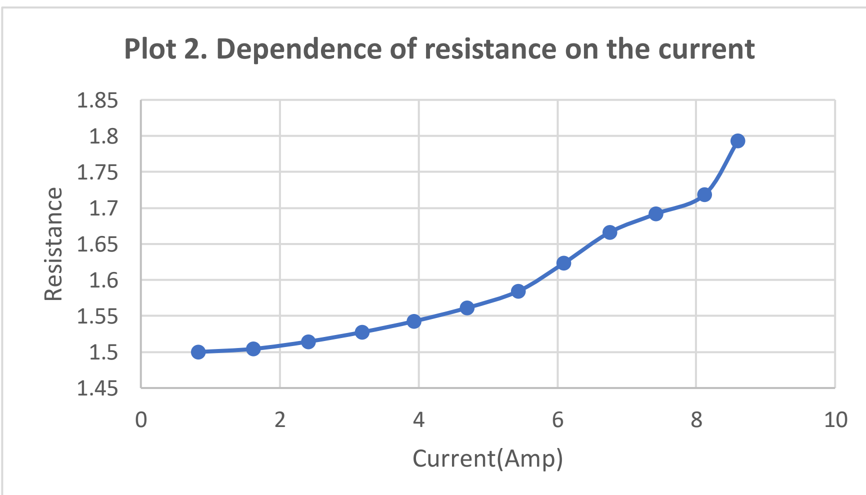
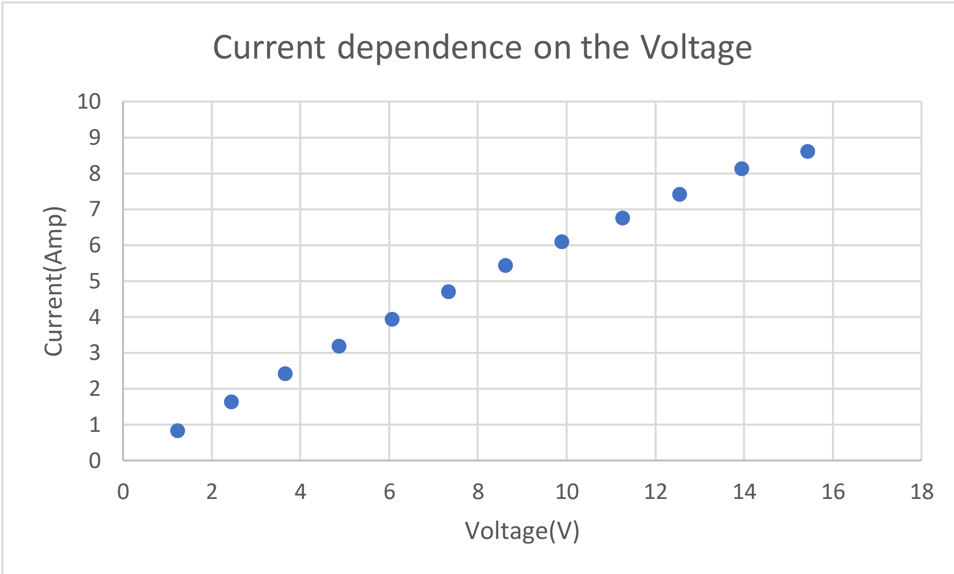


Table 4. Calculating the resistance using by Ohm's law



Plot 4. How the current is depends on the current through the PTC

It is known that resistance is temperature dependent. In examining the graph, an increase in current correlates with an increase in resistance, which can be attributed to the rise in temperature. As temperature elevates, the resistance of the PTC resistor also increases, following the principle that materials with a Positive Temperature Coefficient exhibit higher resistance as thermal energy within the component rises. This behavior illustrates the direct relationship between temperature and resistance for this type of resistor.
According to the theoretical formula, the dependence of resistance on temperature was plotted on a graph. This graph illustrates how resistance varies with changes in temperature, highlighting the direct relationship defined by the PTC resistor's temperature coefficient. Here are the temperature values for each resistance values of a PTC resistor:

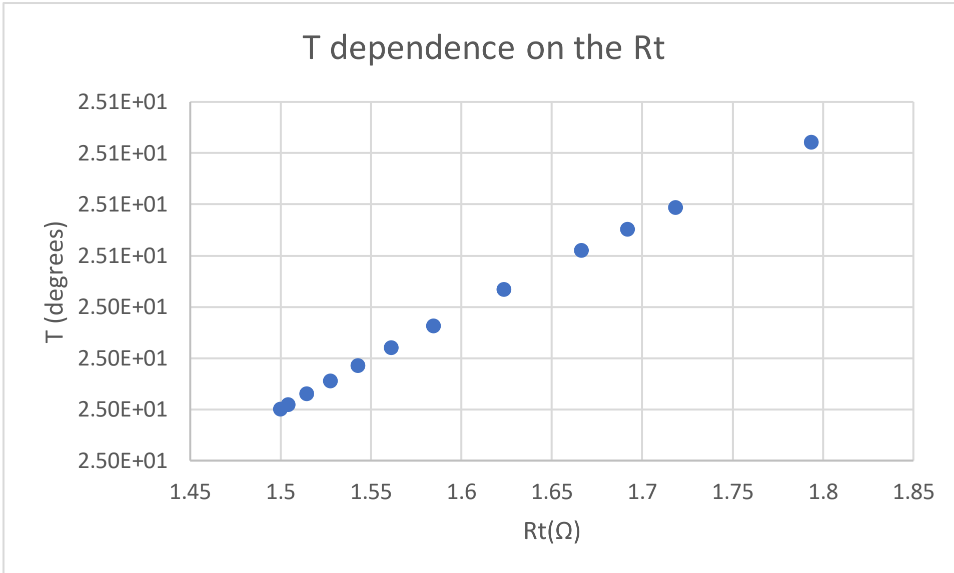
R(Ω)	T
1.5	2.50E+01
1.50431	2.50E+01
1.514487	2.50E+01
1.527473	2.50E+01
1.542588	2.50E+01
1.561277	2.50E+01
1.584559	2.50E+01
1.623462	2.50E+01
1.666223	2.51E+01
1.691779	2.51E+01
1.718473	2.51E+01
1.793701	2.51E+01

To calculate the temperature for each resistances the following formula was used:

$$R_T = R_{25}(1 + \alpha\Delta T)$$

$$T = \frac{R_T - R_{25}}{\alpha R_{25}} + T_{REF}$$

Table 5. Calculated temperatures



Plot 5. How the temperature is depends on the PTC resistance

6 Experiment Part 4

6.1 Experiment part 4: Resistance of a NTC resistor

Used tools and instruments:
- Breadboard, tools box from workbench
- NTC resistor
- TENMA amperemeter
- Power supply ELABO
- ELABO voltmeter

6.2 Experiment part 4 – Setup

- The objective - The objective of this experiment is to examine the temperature-dependent behavior of a Negative Temperature Coefficient (NTC) resistor, where resistance decreases with an increase in temperature. This relationship is described by the formula:

$$R_T = R_{25} e^{\frac{B}{T} - \frac{B}{T_0}}$$

$R_T - resistance\ at\ temperature\ T$

$R_{25} - resistance\ at\ reference\ temperature$

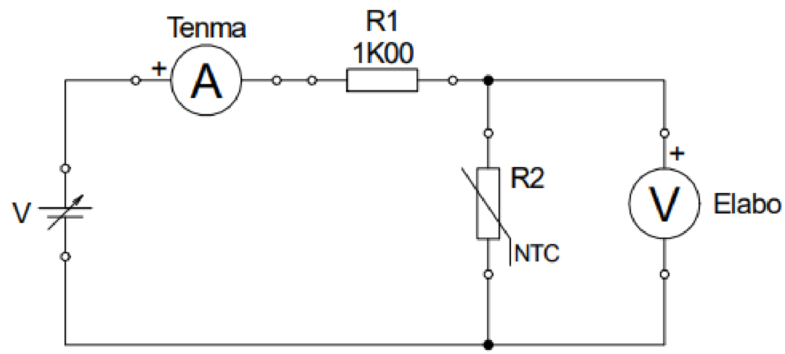
$T - actual\ measured\ temperature$

$T_0 - reference\ temperature\ 298.15\ K$

$B - material\ dependent\ constant\ 3560K$

Temperature changes in this experiment are induced by the power supplied to the component, causing it to self-heat. Observing this behavior allows us to understand the NTC resistor's suitability for applications requiring variable resistance in response to temperature changes.

- **Test Circuit**



$$R_2 = 1\text{k}50\,\Omega$$

Figure 4. Experimental Setup for the Experiment 4

6.3 Experiment Part 4 – Execution and result

Description of the measurement:

- The supply voltage was varied incrementally from 0 V to 24 V in steps of 2 V. At each voltage level, a waiting period of approximately 2 minutes was observed before recording the voltage and current. This waiting time allowed the NTC resistor to reach thermal stability, minimizing fluctuations in the measurements due to self-heating effects. The component was not touched during the measurements to avoid any unintended temperature changes. Voltage and current values were recorded at each step and used to plot a real-time graph, illustrating the relationship between the applied voltage and the corresponding resistance behavior of the NTC resistor.

V(V)	I(A)	R(Ω)
1.244	0.775	1.605161
2.462	1.6	1.53875
3.612	2.448	1.47549
4.8	3.289	1.45941
5.914	4.105	1.440682
6.936	5.2	1.333846
7.48	6.65	1.124812
7.748	8.338	0.92924
8.92	9.286	0.960586
9.487	10.58	0.896692
9.24	12.683	0.728534
9.762	14.492	0.673613

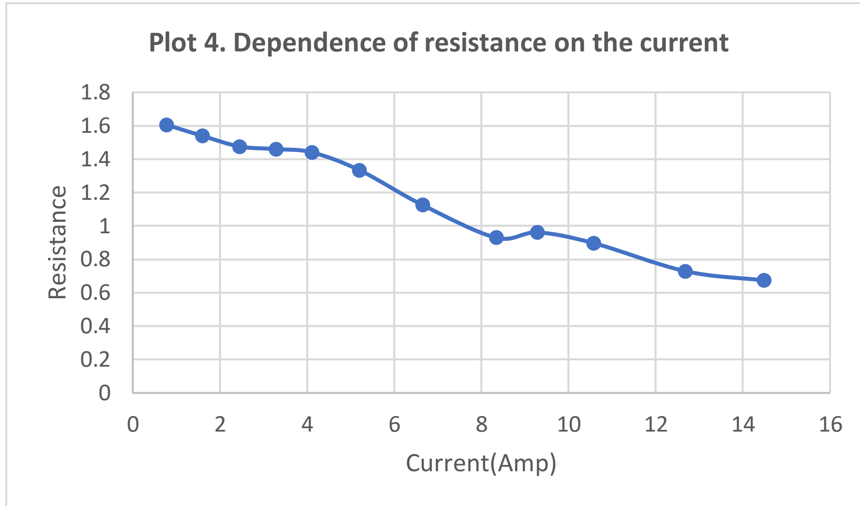
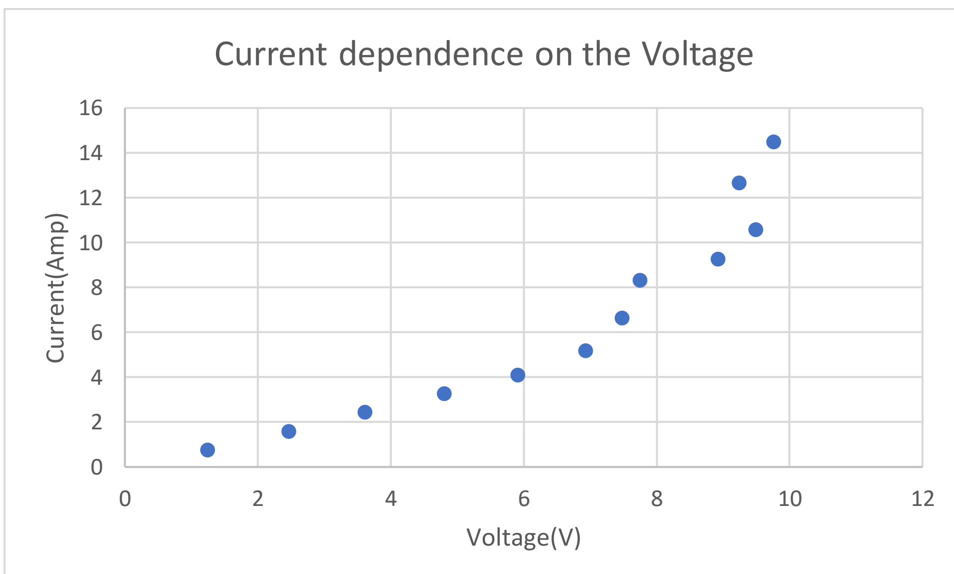


Table 6. Calculating the resistance using by Ohm's law



Plot 7. How the temperature is depends on the NTC resistance

As the current is increased, the temperature of the NTC (Negative Temperature Coefficient) resistor is observed to rise. According to the NTC resistance formula, the resistance is inversely related to temperature. Consequently, as the temperature increases, a decrease in resistance is induced. This behavior highlights the characteristic response of NTC resistors to varying thermal conditions, wherein elevated temperatures result in reduced resistance values. Here are the temperature values for each resistance values of a NTC resistor:

R(Ω)	T(kelvins)
1.605161	296.4676
1.53875	297.51449
1.47549	298.56195
1.45941	298.83658
1.440682	299.16092
1.333846	301.11056
1.124812	305.51517
0.92924	310.60657
0.960586	309.71007
0.896692	311.57582
0.728534	317.34393
0.673613	319.57675

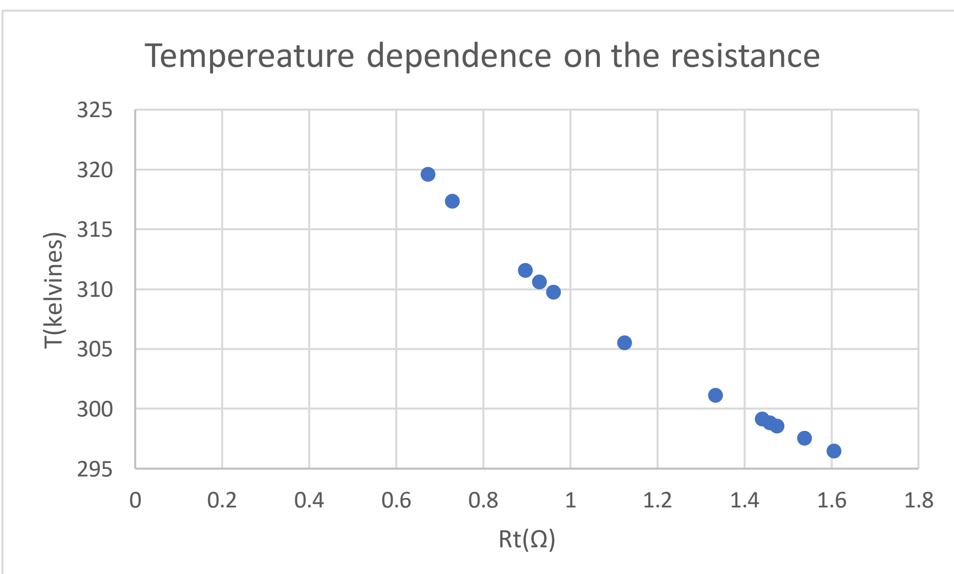
Table 7. Calculated Temperatures

To calculate the temperature for each resistances the following formula was used:

$$R_T = R_{25} e^{\frac{B}{T} - \frac{B}{T_0}}$$

$$T = \frac{B}{\ln\left(\frac{R_T}{R_{25}}\right) + \frac{B}{T_0}}$$

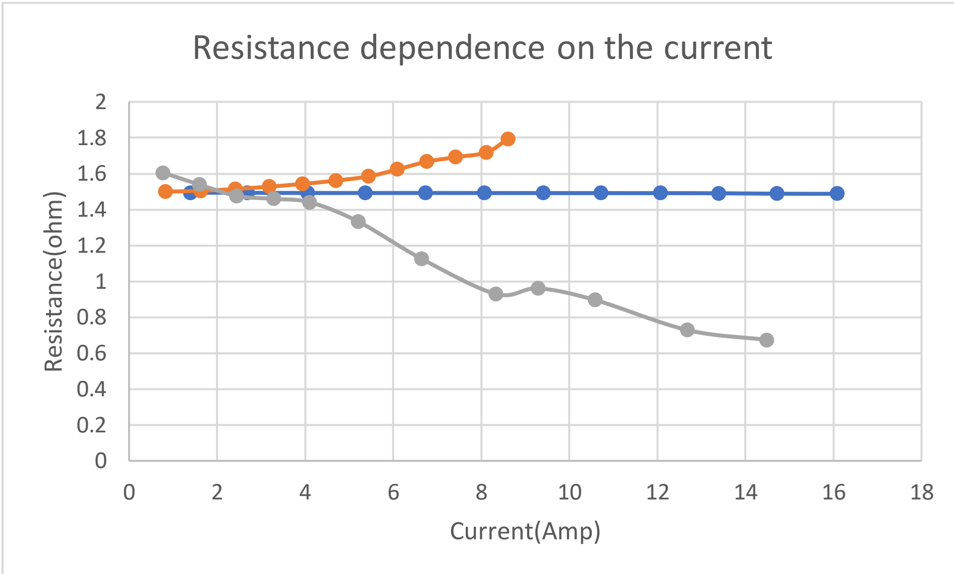
According to the table 7 the following plot was built:



Plot 8. How the temperature is depends on the NTC resistance

7 Evaluation

- Draw the graph R=f(I) for all resistors. Put all three graphs in one diagram.



Blue – Metal film resistor Orange – PTC resistor Gray – NTC resistor

- Do the graphs show the expected behavior?

Metal film resistor - Stability across varying currents and temperatures is observed in the metal film resistor, with constant resistance as current increases.

PTC resistor - In the PTC resistor, resistance is seen to increase gradually due to the rise in temperature when current flows through it.

NTC resistor - For the NTC resistor, a decrease in resistance is noted as the temperature increases, with resistance dropping as the resistor heats up.

- Why might it be dangerous to connect a NTC resistor to higher voltages?

Using an NTC resistor with higher voltages can be hazardous due to the risk of overheating. As the resistor warms, its resistance decreases, allowing more current to pass through and creating additional heat. This feedback loop, called thermal runaway, can result in extreme overheating, potentially damaging the circuit or even posing a fire risk if not carefully managed.

- What kind of resistor is the copper wire? What are the consequences when using it with high currents or with high temperatures?

Copper wire is an excellent low-resistance conductor, but it can overheat under high currents. As the temperature rises, its resistance increases, generating additional heat. This effect can eventually lead to circuit damage or even pose a fire risk.

8 Conclusion

The results of this experiment provided significant insights into the behavior of different resistive components in relation to Ohm's Law. The inherent resistance of the 1-meter copper wire was accurately measured using the Kelvin (4-wire) method, resulting in a value that closely matched theoretical predictions. This confirmed the effectiveness of the measurement technique and highlighted the reliability of copper as a conductor.

In the evaluation of the metal film resistor, a consistent resistance was observed across varying voltage levels. Despite deviations from ideal behavior, the nearly constant resistance under different applied voltages indicated the component's reliability for applications requiring stable performance. The data collected illustrated that, for this type of resistor, the assumption of ohmic behavior holds true within a limited voltage range.

The investigation of the Positive Temperature Coefficient (PTC) resistor revealed a clear correlation between temperature and resistance. As the temperature increased due to self-heating from the applied voltage, a corresponding rise in resistance was documented. This confirmed the expected behavior of PTC materials and emphasized their applicability in scenarios where temperature fluctuations are significant.

Conversely, the behavior of the Negative Temperature Coefficient (NTC) resistor demonstrated an inverse relationship between temperature and resistance. As the supplied power increased the temperature of the NTC resistor, a marked decrease in resistance was recorded. This finding illustrated the unique characteristics of NTC materials, highlighting their potential use in temperature sensing and control applications.

Throughout the experiment, various sources of error were identified and evaluated. The precision of measurements was affected by both instrument and methodical errors. Instrument errors, such as inaccuracies in multimeter readings, were minimized through careful calibration, yet they remained a factor in absolute and relative error calculations. Methodical errors, especially in temperature-dependent resistors, arose from factors like inconsistent heating and cooling rates, which impacted the accuracy of resistance measurements over time. By acknowledging and addressing these potential sources of error, the experiment achieved a more accurate representation of the resistive behaviors of each component, contributing to reliable conclusions about their characteristics.

Overall, the results underscored the importance of understanding the temperature dependence of resistive components. The behaviors observed in both PTC and NTC resistors illustrated the critical role that thermal effects play in electrical circuits. These findings contribute to a deeper understanding of material properties and their implications for practical applications in electrical engineering, paving the way for the informed selection and utilization of resistive components in various circuit designs.

9 References

1. Uwe Pagel, Natural Science Laboratory - General Information for EE Labs, Chapter II, Page 12-19
2. https://en.wikipedia.org/wiki/Ohm%27s_law
3. https://en.wikipedia.org/wiki/Thermistor

10 Appendix – Data from the second experiment of the week

Part 1: A linear network

Vs	14.978 V
Vab	3.3117 V

Part 2: Determine Thevenin's and Norton's parameters

Determine Vth

Vth	7.454 V

Determine I(NO)

Ino	57.06 mA

Determine Rth and Rno

Rth	124.22 Ω
Rno	124.22 Ω

Part 3: Determine Vab using Thevenin's circuit

Vth	7.453 V
Vab	3.3095 V

Part 4: Determine Vab using Norton’s circuit

Ino	57.25 mA
Vab	3.171 V