وزارة التعليـم العالــي و البحــث العلمـــي

DEMOCRATIC AND POPULAR REPUBLIC OF ALGERIA

Ministry of Higher Education and Scientific Research

National Polytechnic School
of Oran Maurice AUDIN

المدرســـة الوطنية المتعددة التقنيات
بوهران- موريس أودان

Department of Preparatory Education in Science and Technology

General Electricity

LAB MANUAL

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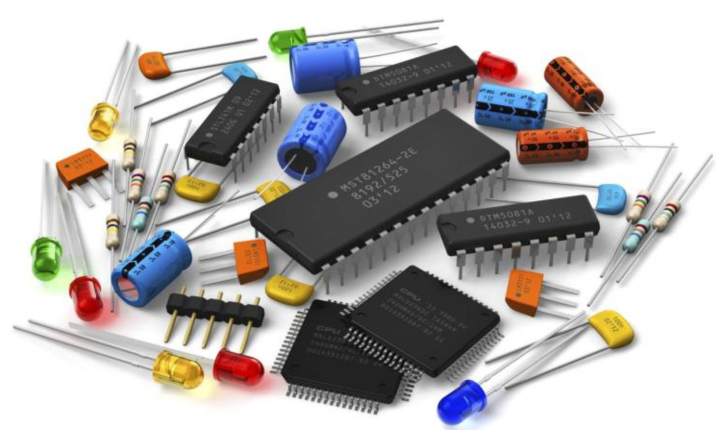

This laboratory manual is intended for second-year preparatory students within the Department of Preparatory Education in Science and Technology (PEST, 3rd Semester) at the National Polytechnic School (NPS) of Oran Maurice AUDIN

Academic Year 2025 / 2026

Preface

This laboratory manual, titled **"General Electricity"**, has been meticulously developed to provide students with a rich and engaging educational resource. While primarily designed for second-year preparatory students within the Department of Preparatory Education in Science and Technology (**PEST, 3rd Semester**) at the **National Polytechnic School (ENP) of Oran Maurice AUDIN**, it corresponds to the official syllabus of the **'General Electricity'** module taught in the second year, this manual will also prove highly beneficial for students in other engineering disciplines.
The fruit of a rigorous synthesis of various bibliographical references and dedicated pedagogical efforts, this manual aims to deliver an essential practical and didactic experience in electronics. The experimental curriculum is designed to guide students through the fundamental laws of electricity, the mastery of circuit analysis methods, and the application of complex models through the study of RLC circuit resonance.

The manual is structured around the following sessions:

- **Experiment No. 1:** Introduction to Equipment and Review
- **Experiment No. 2:** Verification of Ohm's Law
- **Experiment No. 3:** Verification of Kirchhoff's Laws
- **Experiment No. 4:** Analysis of the I-V Characteristics of Two-Terminal Devices
- **Experiment No. 5:** Network Analysis Theorems
- **Experiment No. 6 :** Calculations in Complex Model - RLC Circuit Resonance

To optimize laboratory workflow, each lab instructions sheet is followed by a ready-to-use answer sheet that can serve directly as a lab report. We hope this resource facilitates a deeper understanding of fundamental principles and encourages the practical application of the theoretical knowledge covered.

Experiment No. 1: Introduction to Equipment and Review

1. **Objective**:

The primary goal is to familiarize students with the devices and equipment commonly used in electricity or electronics, while reviewing some important concepts and principles. Here are some specific objectives for this practical work:

- Familiarization with equipment: Introduce students to various electrical or electronic components and devices, such as resistors, voltage sources, multimeters, etc.
- Review of key concepts: Provide a review of important concepts such as the laws of two-terminal component association, the characteristics of electronic components, reading and decoding resistor and capacitor values.
- Simple circuit assembly: Encourage students to assemble simple electrical circuits using available equipment, in order to put their knowledge into practice.
- Measurements and analyses: Invite students to take precise measurements, record data, and analyze the results to better understand circuit behavior.
- Reports and summaries: Encourage students to write reports on their experiments, including observations, results, analyses, and conclusions.

2. **Equipment Used:**

- A dual-output DC power supply.
- Digital multimeters.
- Two incandescent lamps.
- Breadboard, banana-to-banana leads, and multimeter probes.
- Nine resistors: R_1 = 22 Ω; R_2 = 100 Ω; R_3 = 470 Ω; R_4 = 1.5 kΩ; R_5 = 2.2 kΩ; R_6 = 3.3 kΩ; R_7= 10 kΩ; R_8 = 47 kΩ; R_9 = 1 MΩ.
- Three capacitors: C_1 = 1µF; C_2 = 2.2µF; C_3 = 10µF.

Theoretical Part

1. Introduction to Equipment

The electronics laboratory has the following equipment:

Type	Designation	Nomenclature	Use
Power Source	Direct Current (DC)	Voltage/Current	Generate a direct
	Alternating Current (AC)	Low Frequency Generator (LFG)	Generate random functions (sine, square, etc.) with a defined frequency
Measuring Equipment	Ammeter		Measure electric current in A
	Milliammeter		Measure electric current in mA
	Voltmeter		Measure electric voltage in V
	Millivoltmeter		Measure electric voltage in mV
	Millimeter		Measure voltage, current, resistance, etc.
Visualization Equipment	Oscilloscope	4-channel Digital Oscilloscope	Visualize electrical signals as waveforms
		2-channel Oscilloscope	
Breadboards	48 nodes	Build electrical circuits	
Electronic Components	Passive	Resistors	They allow controlling voltages, currents, frequencies, and many other parameters in a wide variety of electronic devices
		Inductors	
		Capacitors	
		Decade Box - Resistance	
		Decade Box - Inductance	
		Decade Box - Capacitor	
		Lamps	
		Diodes	
	Active	Transistors	
Cables and Probes	Cables	Banana/Banana	
		Banana/BNC	
		BNC/BNC	
	Probes	Oscilloscope probes	
		Multimeter probes	

2. Review:

2.1.Resistors:

Resistors are passive electrical components widely used in electrical and electronic circuits to regulate and limit the flow of electric current. They are designed with a specific electrical resistance, measured in ohms (Ω), which opposes the passage of current through the circuit. By controlling current levels, resistors play a crucial role in ensuring the proper operation and protection of electronic devices.

- **Main Function**: The main function of a resistor is to oppose the flow of electric current. They convert electrical energy into heat.
- **Resistance Value**: The resistance value is measured in ohms (Ω).
- **Tolerance**: Resistors have a tolerance, which specifies the margin of error compared to their nominal value.
- **Temperature Coefficient**: Generally expressed in parts per million (ppm) per degree Celsius (°C).
- **Power Rating**: Indicates the amount of heat it can safely dissipate. It is measured in watts (W).
- **Types of Resistors**: Carbon film resistors, metal film resistors, wirewound resistors, thick film resistors, etc.
- **Applications**: Designing filters, adjusting the light intensity of lamps, stabilizing voltages, etc.

2.2. Identification - Decoding Method

To determine the ohmic value of a resistor, one must identify the colors featured on its body and match them to the universal color code.

The international standard **IEC 60757**, entitled *Code for designation of colors* (1983), defines the color coding system applied to resistors, capacitors, and other electronic components. This system uses colored bands painted around the body of the resistor to indicate its resistance value (in ohms) and its tolerance. Resistors generally come in three configurations: **4-band, 5-band, and 6-band** models.

Here is how to decode a resistor's color bands:

1. Orient the resistor correctly: First, position the resistor in the right direction. Generally, it features a gold or silver band, which must be placed on the far right. In other cases, the widest band should be placed on the right, or the band printed closest to an edge must be positioned on the far left.

2. Identify the Tolerance Position: The last band on the right indicates the resistor's tolerance.

3. Identify the Multiplier Position: The band located immediately to the left of the tolerance band indicates the multiplier (×10^x). Each color corresponds to a specific power of 10.

4. Identify the Significant Digits: The first two (or three) bands on the left represent the significant digits. Each color corresponds to a specific numerical value.

5. Calculate the Resistance Value: Using the data gathered from the colors, combine the significant digits in order and multiply them by the multiplier value.

6. Apply the Tolerance: Based on the color of the tolerance band, determine the acceptable margin of error. For example, a gold band indicates a tolerance of ±5%.

By following this method, you can easily decode a resistor's colors to determine its value and tolerance. This system is universally used in electronics and helps ensure you select the appropriate component for your circuits, Table 1 summarizes the resistor color code.

Table 1: Resistor Color Code Note: 5-band, do not include a temperature coefficient column (Band 6).

Color	**Color Name**	**1st digit 1st stripe**	**2nd digit 2nd stripe**	**3rd digit 3rd stripe**	**Multiplier 4th stripe**	**Tolerance 5th stripe**
	Black	0	0	0	x1	-
	Brown	1	1	1	x10	1%
	Red	2	2	2	x100	2%
	Orange	3	3	3	x1000	3%
	Yellow	4	4	4	x100000	4%
	Green	5	5	5	x1000000	-
	Blue	6	6	6	x10000000	-
	Violet	7	7	7	-	-
	Grey	8	8	8	-	-
	White	9	9	9	-	-
	Gold	-	-	-	x0.1	5%
	Siliver	-	-	-	x0.01	10%

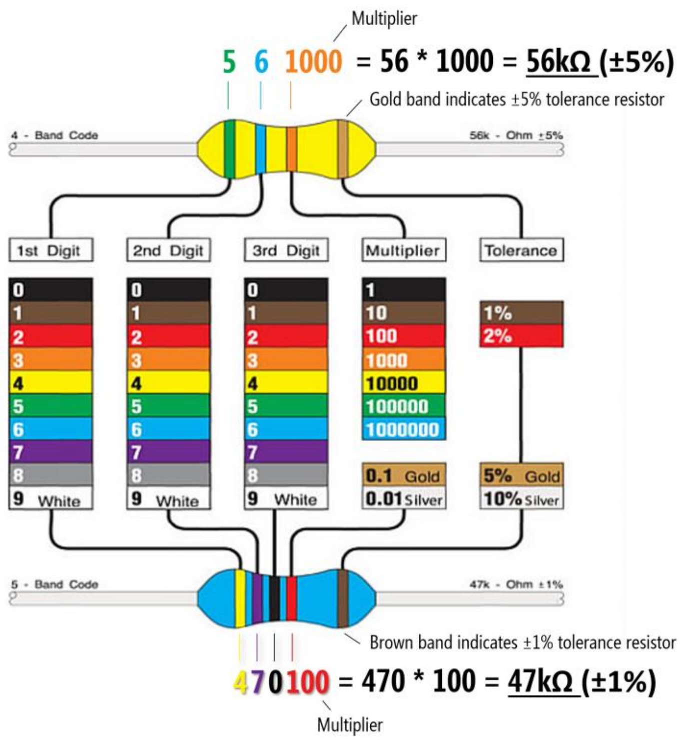

Figure 1.1. Resistor color decoding diagram, illustrating two examples (4-band and 5-band resistors).

2.3.Capacitors:

Capacitors are passive electrical components extensively employed in electronic circuits for energy storage and release. They store electrical energy in the form of an electric charge and can rapidly discharge this energy when required by the circuit. Owing to their ability to store and transfer energy, capacitors are essential elements in filtering, coupling, timing, and energy-management applications.

- **Function**: Used to store electrical energy and release it later in a circuit.
- **Structure**: Composed of two conductive plates separated by a dielectric material.

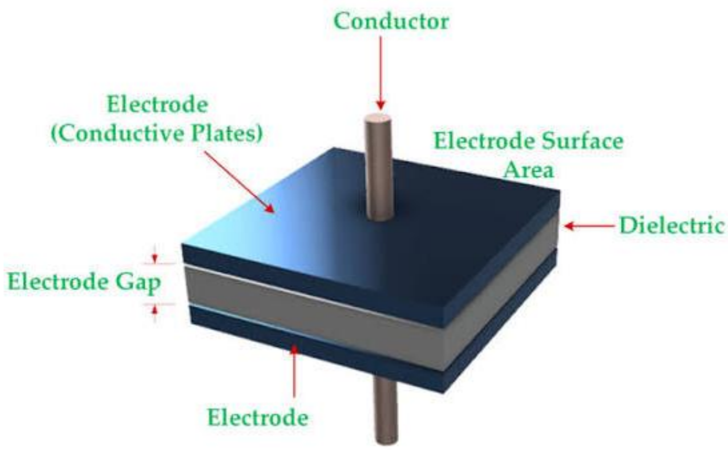

Figure 1.2. Structure of a Capacitor

- **Capacitance**: Measured in farads (F), indicates its ability to store electrical energy.
- **Voltage Rating**: Maximum nominal voltage to which they can be safely subjected.
- **Polarity**: Some capacitors are polarized and must be connected in the correct direction.

Figure 1.3. Capacitor Symbols.

- **Dielectric**: Common types include polyester, polypropylene, aluminum, tantalum, and ceramic.

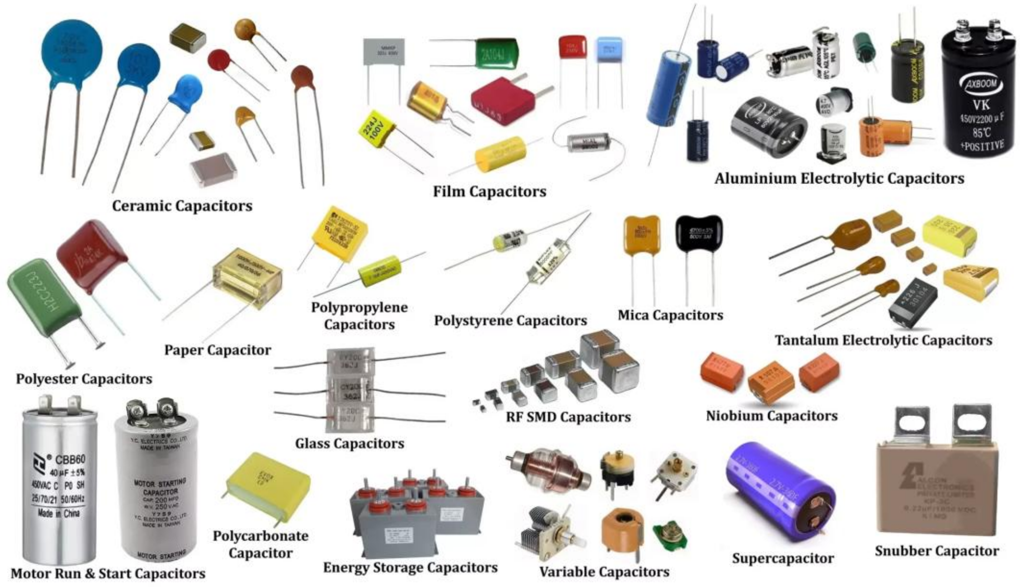

Figure 1.4. Common Types of Capacitors.

- Applications: Power supplies, filters, timer circuits, amplifiers, radios, televisions, etc.
- Charge and Discharge Time: Store energy quickly when charged and release it quickly when discharged.

➢ The information typically provided on a commercial capacitor includes the following:

1. **Capacitance** (C): This is the primary value of the capacitor, expressed in farads (F), and commonly indicated in submultiples such as microfarads (µF), nanofarads (nF), or picofarads (pF). For example, a capacitor may be rated at 10 µF.
2. **Rated Voltage** (V): This represents the maximum voltage that the capacitor can withstand safely without suffering damage. It is expressed in volts (V). For instance, a capacitor may have a rated voltage of 25 V.
3. **Tolerance**: Tolerance specifies the permissible deviation of the actual capacitance from its nominal value and is generally expressed as a percentage. For example, a tolerance of ±10% indicates that the actual capacitance may vary between 90% and 110% of the specified value.

Figure 1.5. Example of Information Printed on a Commercial Electrolytic Capacitor

4. **Polarity** (for polarized capacitors): Polarized capacitors, such as electrolytic capacitors, are marked to indicate their positive (+) and negative (−) terminals. Correct polarity must be observed during circuit assembly.
5. **Maximum Operating Temperature**: Some capacitors are marked with their maximum operating temperature, typically expressed in degrees Celsius (°C), such as 85°C or 105°C.
6. **Marking Code**: Particularly in small capacitors, capacitance and voltage ratings may be represented by numerical codes. For example, the code "104" corresponds to 100 nF, where the first two digits represent the significant figures and the third digit indicates the multiplier.

1.4. Connection of passive two-terminal elements

1.4.1. Linear passive two-terminal elements

Three passive two-terminal components are commonly used in electrical circuits.

Table 2: Characteristics of Elementary Passive Components

Passive Component	**Fundamental Law**	**Schematic**	**Steady-State (DC) Behavior**
Resistor R (Ω) **Conductance G = 1/R** **(S) [siemens : (Ω^{-1})]**	*u(t) = R · i(t)* *i(t) = G · u(t)* (Ohm's Law)	i(t) R ──►─▭─ ──◄── u(t)	u and i are constants: U = R · I P(t) = U · I = R · I^2 = U^2/R in watts (W)
Capacitor C: **Capacitance (F/Farad)**	*i(t) = C · du(t)/dt*	i(t) C ──►─┤ ├── ──◄── u(t)	u is constant and i is zero: The capacitor behaves as an open circuit (open switch).
Inductor L : **Inductance (H/Henry)**	*u(t) = L · di(t)/dt*	i(t) L ──►─∩∩∩─ ──◄─── u(t)	i is constant and u is zero: • The ideal inductor is equivalent to a wire (short-circuit).

1.4.2. Association Laws of Passive Components

➢ **Resistors (R):**

- In series: Resistances add up directly: $R_{eq} = R_1 + R_2 + ... + R_n = \Sigma R_i$
- In parallel: Conductances add up; the reciprocal of the equivalent resistance is equal to the sum of reciprocals:
  $1/R_{eq} = 1/R_1 + 1/R_2 + ... + 1/R_n = \Sigma 1/R_i$
  For two resistors in parallel: $R_{eq} = (R_1 \cdot R_2) / (R_1 + R_2)$

➢ **Capacitors (C):**

- In series: Behavior is inverse to resistors:
  $1/C_{eq} = 1/C_1 + 1/C_2 + ... + 1/C_n = \Sigma 1/C_i$
- In parallel: Capacitances add up directly to increase total capacitance: $C_{eq} = C_1 + C_2 + ... + C_n = \Sigma C_i$

➢ **Inductors (L):**

- In series: Inductances behave like resistors and add up directly: $L_{eq} = L_1 + L_2 + ... + L_n = \Sigma L_i$

- In parallel: The reciprocal of the equivalent inductance adds up:

  $1/L_{eq} = 1/L_1 + 1/L_2 + ... + 1/L_n = \Sigma\ 1/L_i$

1.4.3. Tolerance Calculation Rules for Equivalent Resistors:

When calculating the equivalent resistance of a network, understanding tolerance propagation is essential for ensuring hardware reliability. Two mathematical models are standard in industrial electronics: Worst-Case Analysis (deterministic bound) and Statistical Analysis (RSS) (probabilistic optimization).

a. **The Worst-Case Approach (Deterministic):**

This approach assumes that all part tolerances vary simultaneously to their most unfavorable operational extremes.

• Series Combination ($R_{eq} = R_1 + R_2 + ...$):

Absolute tolerance: $\Delta R_{eq} = \Delta R_1 + \Delta R_2 + ... + \Delta R_n$

Relative tolerance: $t_{eq} = (R_1 \cdot t_1 + R_2 \cdot t_2 + ...) / (R_1 + R_2 + ...)$

• Parallel Combination ($1/R_{eq} = 1/R_1 + 1/R_2 + ...$):

Absolute tolerance: $\Delta Req = R_{eq}^2 \cdot \Sigma\ (\Delta R_i / R_i^2)$

Relative tolerance (for two resistors): $t_{eq} = (R_2 \cdot t_1 + R_1 \cdot t_2) / (R_1 + R_2)$

b. **The Statistical Approach (Root Sum Square - RSS):**

This approach assumes components are chosen randomly and follow a Gaussian (normal) distribution. It calculates a realistic, tighter tolerance margin.

• Series Combination:

Absolute tolerance: $\Delta R_{eq} = \sqrt{[(\Delta R1)^2 + (\Delta R2)^2 + \ldots + (\Delta Rn)^2]}$

Relative tolerance: $t_{eq} = \sqrt{[(R1 \cdot t1)^2 + (R2 \cdot t2)^2 + \ldots]} / (R_1 + R_2 + ...)$

• Parallel Combination:

Relative tolerance (for two resistors): $t_{eq} = \sqrt{[(R2 \cdot t1)^2 + (R1 \cdot t2)^2]} / (R_1 + R_2)$

Practical Engineering Example:

Let's analyze an exact practical scenario using two distinct resistors:

• Resistor 1 (R_1): 220 Ω ± 5% │ Absolute margin: $\Delta R_1 = 220 \times 0.05 = 11\ \Omega$

• Resistor 2 (R_2): 470 Ω ± 1% │ Absolute margin: $\Delta R_2 = 470 \times 0.01 = 4.7\ \Omega$

Table 3: Comparative Results of Tolerance Propagation

Configuration	Nominal Value	Worst-Case Result	Statistical (RSS) Result
Series Association **$R_{eq} = R_1+R_2$**	690 Ω	± 2.28% (ΔR_{eq} = 15.7 Ω)	± 1.73% (ΔR_{eq} = 11.96 Ω)
Parallel Association **$R_{eq} = R_1 \cdot R_2 /(R_1+R_2)$**	149.86 Ω	± 3.73% (ΔR_{eq} = 5.58 Ω)	± 3.42% (ΔR_{eq} = 5.13 Ω)

❖ **Crucial Design Insights**

- In a parallel configuration, the equivalent resistance is heavily biased toward the smaller resistor value (R_1 = 220 Ω). Since R_1 has a poor tolerance (5%), it degrades the overall network's precision, pushing it up to 3.73%.
- In a series configuration, the largest resistor dictates the weight. Because the larger resistor (R_2 = 470 Ω) possesses high accuracy (1%), it effectively absorbs and mitigates the error introduced by R_1, keeping the final system tolerance exceptionally stable at 2.28%.

Practical Part

1. Association of passive components:

1.1. Circuit setups and Questions:

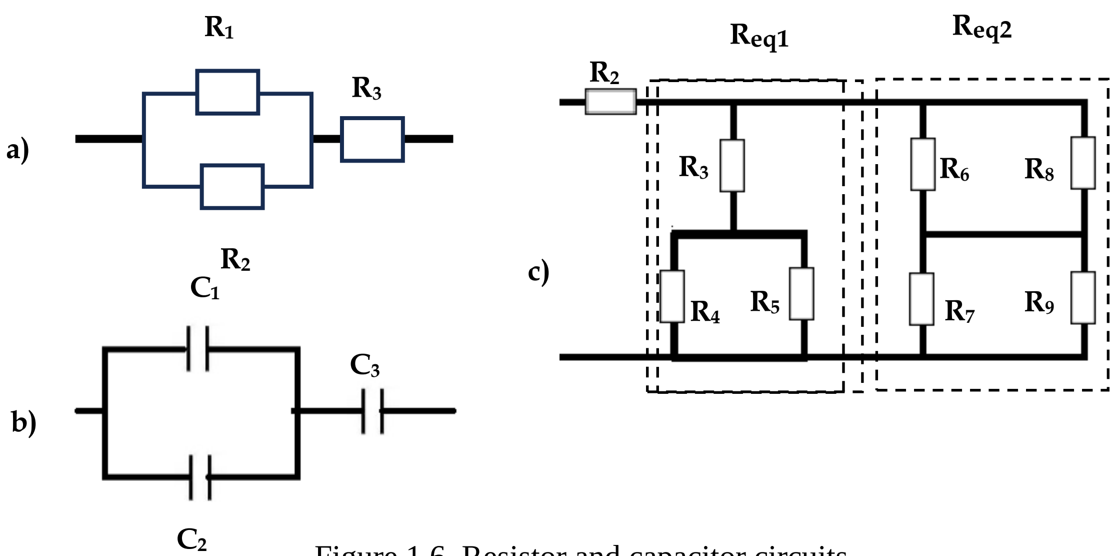

Figure 1.6. Resistor and capacitor circuits

1. Set up the three circuits and measure the equivalent resistance for each. For circuit (c), measure the value of $R_{eq}1$ and $R_{eq}2$.

$R_{eq}(a)$ = ... $C_{eq}(b)$ = ...

$R_{eq}1$ = ... $R_{eq}2$ = ...

$R_{eq}(c)$ = ...

3. Verify the association laws of passive components for the three circuits and calculate the equivalent tolerance Teq for circuit (a).

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3. Compare all measured values with the theoretical values. Conclude.

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4. Identify the potential sources of error in your measurements (such as the internal resistance of the multimeter, wire resistance, or temperature variations) and explain how they might affect your experimental results.

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5. If a constant DC voltage of 12V is applied across the equivalent resistance of circuit (a), calculate the total current flowing through the circuit and the electrical power dissipated by each resistor.

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Experiment No. 2: Verification of Ohm's Law

1. Objectives:

- Experimental verification: Demonstrate through experiment the validity of Ohm's law for an ohmic conductor (resistor), namely the linear relationship $U = R \cdot I$.
- Study of the characteristic curve: Plot and analyze the characteristic curve $U = f(I)$ to observe that it is a straight line passing through the origin.
- Graphical determination of a quantity: Determine the value of the resistance R by measuring the slope (gradient) of the resulting line.
- Circuit assembly: Learn to wire a simple electrical circuit containing an adjustable DC power supply, a resistor, and connecting wires.
- Equipment management: use a digital multimeter, choose the correct mode (DC), and select the appropriate range to avoid damaging the device.
- Data collection and processing: Create a clear measurement table by varying the power supply voltage in regular increments.
- Comparison Analysis: Compare the graphically determined resistance value with its nominal value (given by the color code or measured directly with an ohmmeter).

2. Equipment Used:

- One dual-output DC power supply
- Two digital multimeters
- Breadboard, banana-to-banana leads, and multimeter probes
- Nine resistors: R_1=100 Ω; R_2=330 Ω; R_3=1kΩ; R_4=2.2 kΩ; R_5=3.3 kΩ; R_6=10 kΩ; R_7=47 kΩ; R_8=100 kΩ.

Theoretical Part

1. **Characteristic Curve of a Resistor (Ohm's Law)**

The characteristic curve of an electrical resistor obeys Ohm's law, which states that the voltage across the resistor is directly proportional to the current flowing through it. This fundamental relationship is expressed by the formula: $U = R \cdot I$

Where:

- U represents the voltage (in Volts, V) across the terminals of the resistor.
- I represents the intensity of the electric current (in Amperes, A) flowing through the resistor.
- R is the electrical resistance of the component (in Ohms, Ω).

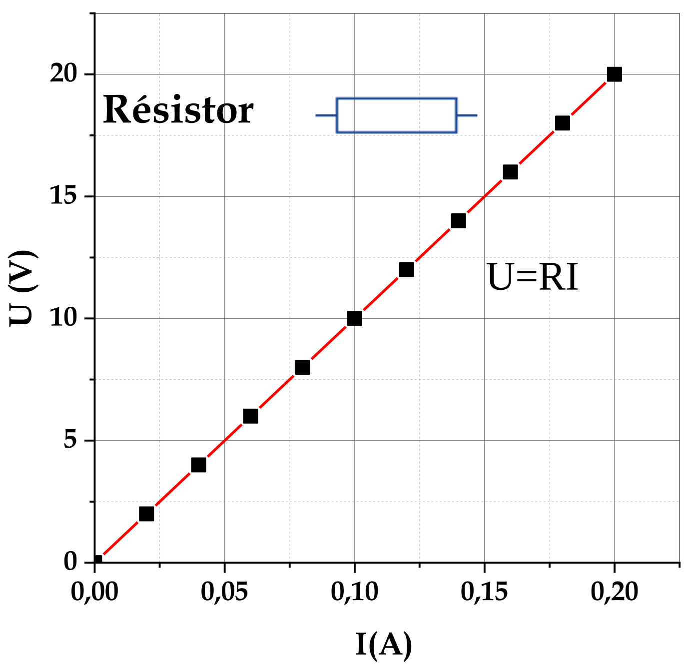


Figure 2.1. Characteristic curve of a 100 Ω resistor

The current–voltage (I–V) characteristic of a resistor is linear, meaning that the voltage across the resistor is directly proportional to the electric current flowing through it. This property reflects the fundamental nature of Ohm's law, according to which electrical resistance is constant, and the ratio between voltage and current remains constant for a given resistor.

It should be noted that the characteristic curve of a resistor is always a straight line passing through the origin. The slope (gradient) of this line corresponds to the value of the resistance itself

Practical Part

Verification of Ohm's Law:

Power the following circuit with a voltage source E = 15V.

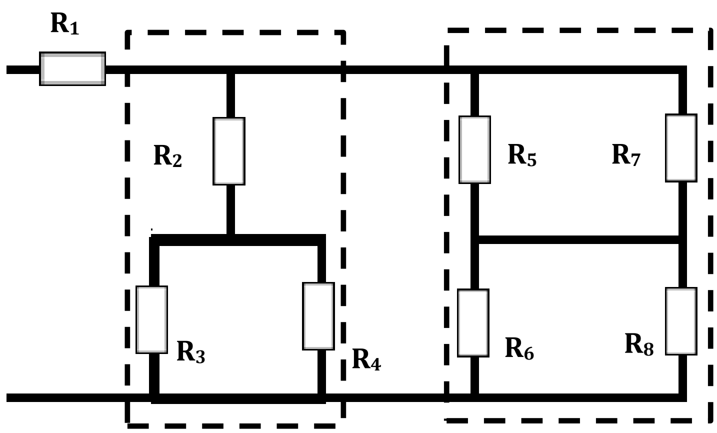


Figure 2.2

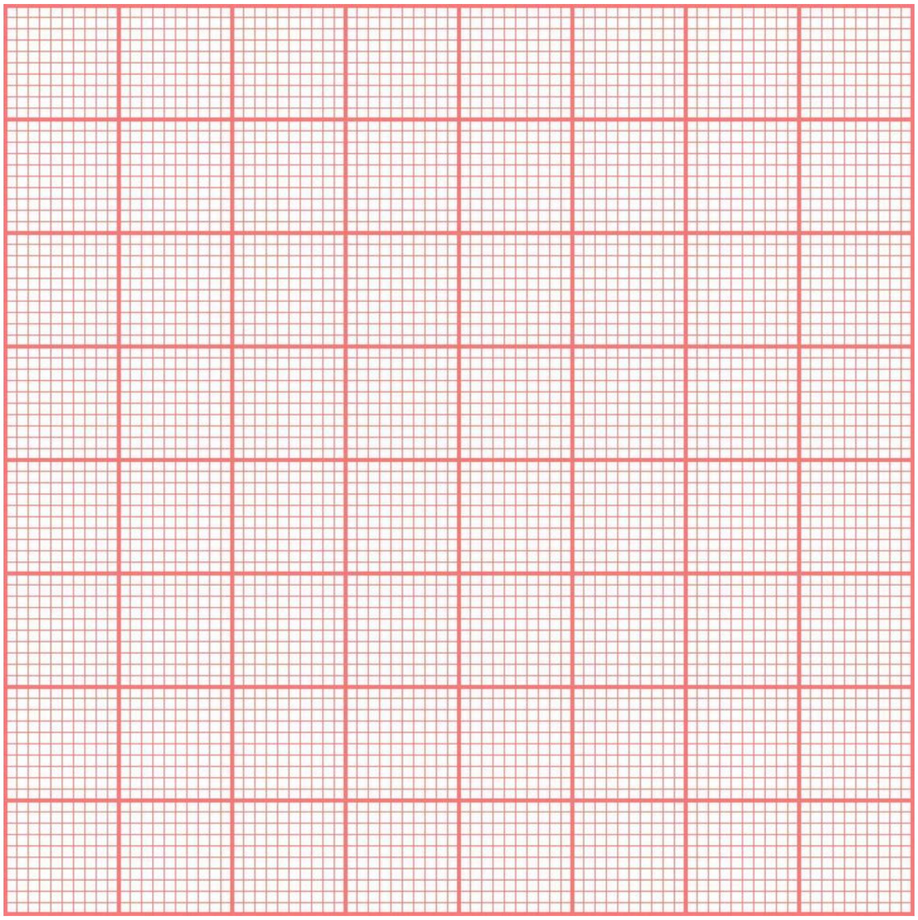
1. Measure the current I_0 supplied by the source using the multimeter in amperemeter mode. Deduce the equivalent resistance of the circuit.

   I_0=……………………………...,   Req= ……………………………………..

2. Compare Req with the calculated value : ………………………………………………………
3. Using the multimeter with its probes, measure the voltage across the different resistors selected in the table below.
4. Fill in the table by applying Ohm's law

Load	R_2	R_3	R_4	R_5	R_6
Measured voltage U(V) (mA)	…………	…………	…………	…………	…………
Deduced current I (mA)	…………	…………	…………	…………	…………

- What is the shape of the resulting curve? Justify why this two-terminal component is classified as linear and passive.
- Graphically determine the value of the resistance R by calculating the slope (gradient) of the straight line.



- Compare this experimental value with the nominal value (read via the color code or measured directly with an ohmmeter).

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Experiment No. 3: Verification of Kirchhoff's Laws

1. **Objectives**:

- Understanding and application of Kirchhoff's laws: Apply these laws to solve complex electrical circuits, using calculation techniques to determine currents and voltages.
- Experimental verification: Use real electronic components to experiment with circuits and verify that Kirchhoff's laws hold by measuring currents and voltages.

2. **Equipment Used**

- A dual-output DC power supply.
- Two digital multimeters.
- Five resistors: 10 (or 22) Ω; 330 (or 470) Ω; 1 kΩ, 2.2 kΩ, 10 kΩ.
- Two incandescent lamps.
- Breadboard, banana-to-banana leads, and multimeter probes.

Theoretical Part

1. KIRCHHOFF'S CIRCUIT LAWS

A linear electrical network (electrical circuit) is a combination of passive elements and active elements, connected together by conductors assumed to have no resistance.

- Node: Point where at least 3 two-terminal components meet (e.g., A, B, C...).
- Branch: Set of two-terminal components in series placed between two nodes (e.g., AC, AD, CB, ...).
- Mesh: Closed loop consisting of at least 2 branches (e.g., ACDA, CBDC, ...).

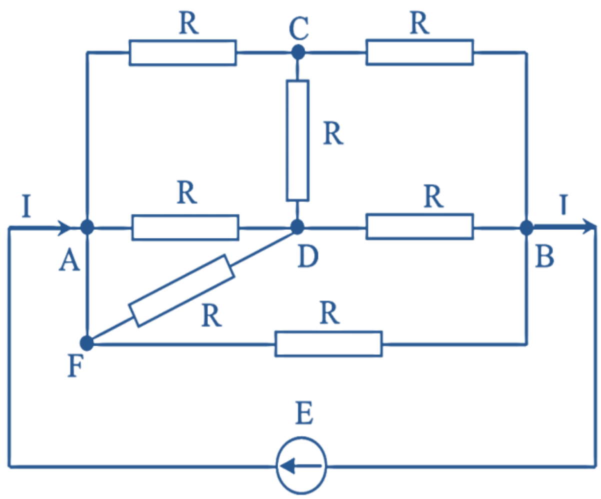


Figure 3.1. Example of a linear electrical circuit

2. Theoretical Foundation:

2.1. Kirchhoff's Current Law (KCL - Node Law)

Principle: Conservation of electrical charge.

There is no accumulation of electrical charges at a node. The sum of the currents entering a node is strictly equal to the sum of the currents leaving it.

Mathematical Expression:

$$\sum I_{in} = \sum I_{out}$$

$$I_1 + I_2 = I_3 + I_4 + I_5$$

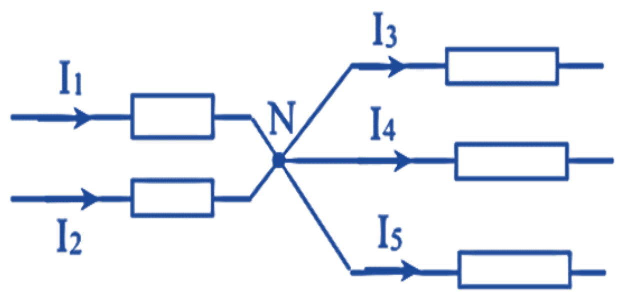


Figure 3.2 : Illustration of the Node Law

2.2.Kirchhoff's Voltage Law (KVL - Loop Law)

Principle: Conservation of energy.

In a closed loop (or mesh) of a circuit, the algebraic sum of the potential differences (voltages) along this loop is exactly zero.

Mathematical Expression:

$$\sum_{i=1}^{n} U_i = 0$$

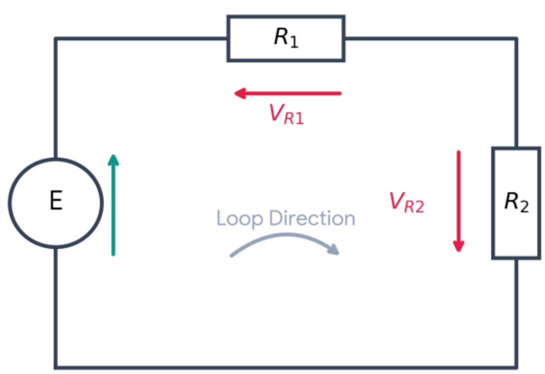
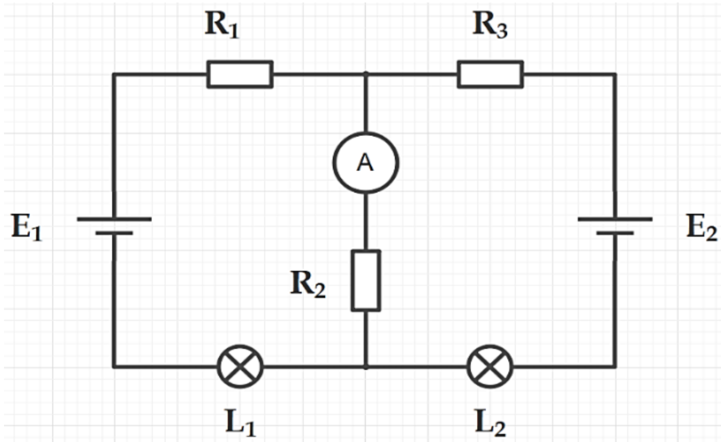


Figure 3.3 : Illustration of the Loop Law (E - V_{R1} - V_{R2} = 0)

Practical Part



Consider the following circuit: $R_1 = 330\ \Omega$, $R_2 = 1\ k\Omega$, $R_3 = 10\ \Omega$, $E_1 = 30$ V, and $E_2 = 25$ V.

PART I

1. When you set up the circuit and power it on, what observations can you make? Formulate a hypothesis.

Observations:

……..

Hypothesis: ....

2. Use a multimeter and its probes to measure the voltages across each component, identifying the polarity as well as the direction of the current and voltage for each component on the figure. Fill in the following table:

Voltage	E_1	E_2	$U(R_1)$	$U(R_2)$	$U(R_3)$	$U(L_1)$	$U(L_2)$
Measured value (V)							

3. Read on the generator's screen the currents I_1 and I_2 supplied by E_1 and E_2 respectively, as well as the current I flowing through R_2, displayed on the ammeter. Fill in the following table:

Current	I_1	I_2	I
Measured value (mA)			

4. Verify Kirchhoff's Voltage Law (loop law). Verify Kirchhoff's Current Law (node law). Then, demonstrate the validity of your hypothesis.

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5. Determine the resistances r_1 and r_2 of L_1 and L_2 respectively, using the V-I characteristic graph plotted in the previous section. Conclude.

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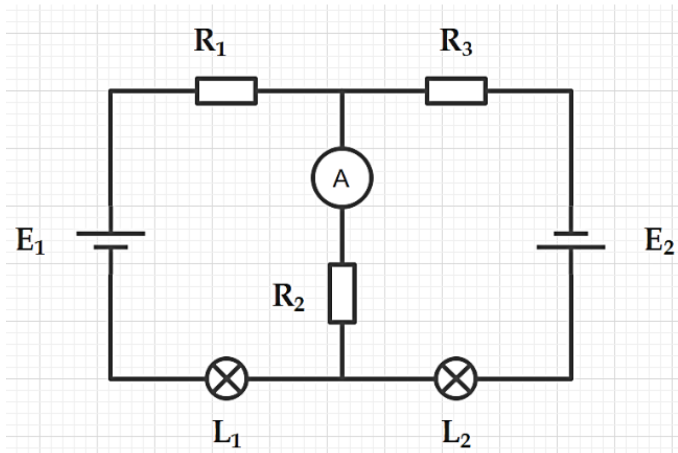
PART II

Reverse the polarity of E_2 and repeat the questions from Part I.



Observations:

....

Hypothesis: ....

Demonstrate the validity of your hypothesis using the necessary measurements:

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....

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PART III

Keeping the previous circuit configuration (Part II), swap the positions of resistor R2 and lamp L1. What observations can you make? Formulate a hypothesis.

Observations:

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Hypothesis:

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....

Verify your hypothesis using the necessary measurements:

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PART IV

Maintaining the last setup (Part III):

1. By adding a 10 kΩ resistor R_4 in parallel with the voltage source E_1, what observations can you make? Observations:

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2. By adding a 2.2 kΩ resistor R_5 in series with R_3, what observations can you make? Observations:

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3. Demonstrate both cases without performing any calculations.

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4. Starting from setup II, please indicate the optimal arrangement of the three resistors to ensure the exclusive lighting of lamp L_1.

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Experiment No. 4: Analysis of the I-V Characteristics of Two-Terminal Devices

1. **Objectives:**

- Understanding the characteristics of the incandescent lamp: Understand the operation of the incandescent lamp, including the relationship between the voltage (U) and the current (I) flowing through the lamp.

- Study of non-linear characteristics: Observe and analyze the non-linear behavior of the incandescent lamp, particularly its U=f(I) characteristic, which shows an increase in resistance with the increase in temperature.

- Calculation of dynamic resistance: Determine the dynamic resistance of the incandescent lamp using Ohm's law for different operating points.

- Measurements and instrumentation: Learn to use measuring instruments such as voltmeters, ammeters, and multimeters to take accurate measurements.

- Error analysis: Understand the potential sources of error in electrical measurements and learn how to minimize them.

2. **Equipment used:**

- A dual-output DC power supply.

- Two digital multimeters.

- Rheostat with R_{max}=1 (or 10) kΩ.

- Two incandescent lamps.

- Breadboard, banana-to-banana leads, and multimeter probes.

Theoretical Part

1. U = f(I) Characteristic of Two-Terminal Components:

The current-voltage characteristic of a two-terminal component is the graphical representation of the variation of the voltage 'U' across its terminals as a function of the intensity of the current 'I' flowing through it. It is denoted as U = f(I). It allows us to define the properties of the component in question and facilitates the determination of the current flowing through it when the voltage across its terminals is known, or vice versa. Furthermore, it provides a means to distinguish whether the component is passive or active.

A component is considered passive when its static characteristic passes through the origin O (i.e., $U_0 = 0$ and $I_0 = 0$). On the other hand, a component is classified as active if its static characteristic does not pass through the origin O (i.e., $U_0 \neq 0$ and $I_0 \neq 0$).

2. Characteristic of an Incandescent Lamp:

General Overview:

Incandescent lamps are a type of electric lamp that produces light by heating a metal filament to a high temperature until it emits visible light. The main characteristics of an incandescent lamp include:

• **Filament**: Incandescent lamps use a tungsten filament as their central element. This filament is heated by the electric current, causing it to incandescer and emit visible light.

• Energy Efficiency: Incandescent lamps are less energy-efficient compared to other types of lamps because they convert a large portion of electrical energy into heat rather than light. Therefore, they are relatively inefficient.

Figure 4.1. Incandescent lamp

• **Limited Lifespan**: Incandescent lamps have a limited lifespan compared to other lighting technologies, such as fluorescent lamps or LEDs. They tend to burn out more quickly due to the fragility of the filament.

• **Reduced Availability**: Many countries have phased out incandescent lamps in favor of more energy-efficient light sources due to their low efficiency. Consequently, they are increasingly less available on the market.

• **Environmental Impact**: Incandescent lamps are less environmentally friendly than other energy-efficient options due to their high energy consumption and short lifespan. They also produce more heat, which can lead to an increase in energy consumption for air conditioning under certain conditions.

In summary, although incandescent lamps were widely used in the past due to their warm light and dimming capability, they have become less popular due to their energy inefficiency and environmental impact. Nowadays, fluorescent lamps and LEDs are more commonly used for lighting due to their better energy efficiency and longer lifespan.

3. U = f(I) Characteristic of the Lamp

The characteristic curve U = f(I) of an incandescent lamp is not a straight line passing through the origin like that of a resistor. The difference in filament temperature between the initial value (0 V) and the final value (10 V) is very significant, which explains why the filament does not behave like an ohmic conductor. The resistance of the studied lamp varies from 4 Ω when cold up to ~70 Ω when hot. All metallic wires exhibit such a U=f(I) characteristic if their temperature varies: their electrical resistance increases with temperature.

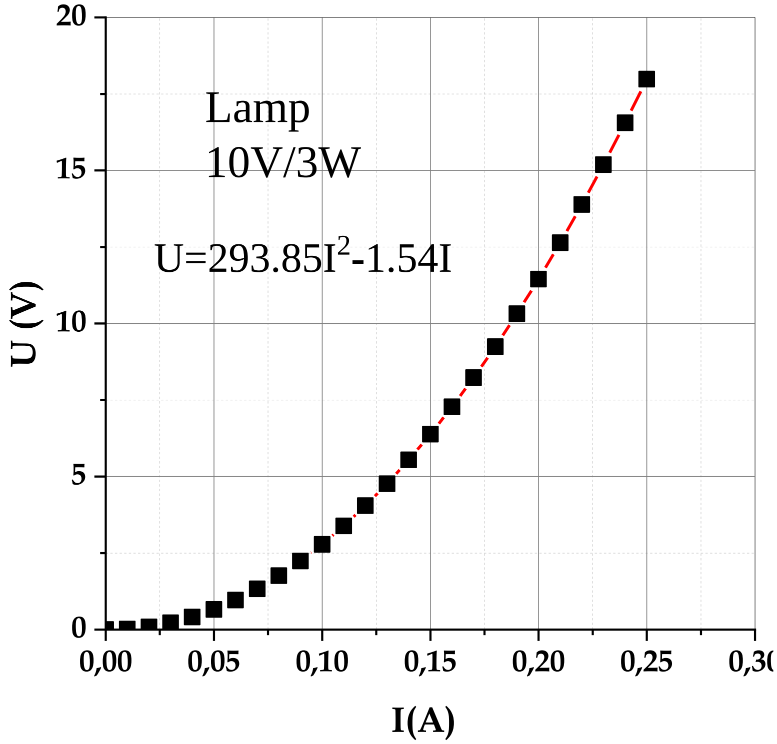


Figure 4.2. Example of a U = f(I) characteristic of an incandescent lamp

4. Characteristic of a DC Voltage Generator

A voltage generator is recognized by its unique property of maintaining a voltage across its terminals when it is isolated (without an external circuit), i.e., in the absence of current. This voltage constitutes its electromotive force (emf), E. When a generator supplies current, the voltage across its terminals decreases progressively. The characteristic curve is practically a straight line with the equation:

$$\mathbf{U = E - r \times I}$$

Where:

• E is the electromotive force (emf) or open-circuit (no-load) voltage.

• r is the internal resistance of the power supply/cell.

The larger this resistance, the greater the voltage drop as the current intensity increases. Generators generally have a much lower internal resistance than electrochemical cells (batteries). The characteristic of a generator does not pass through the origin because a voltage exists even in the absence of current. Therefore, generators are active two-terminal components.

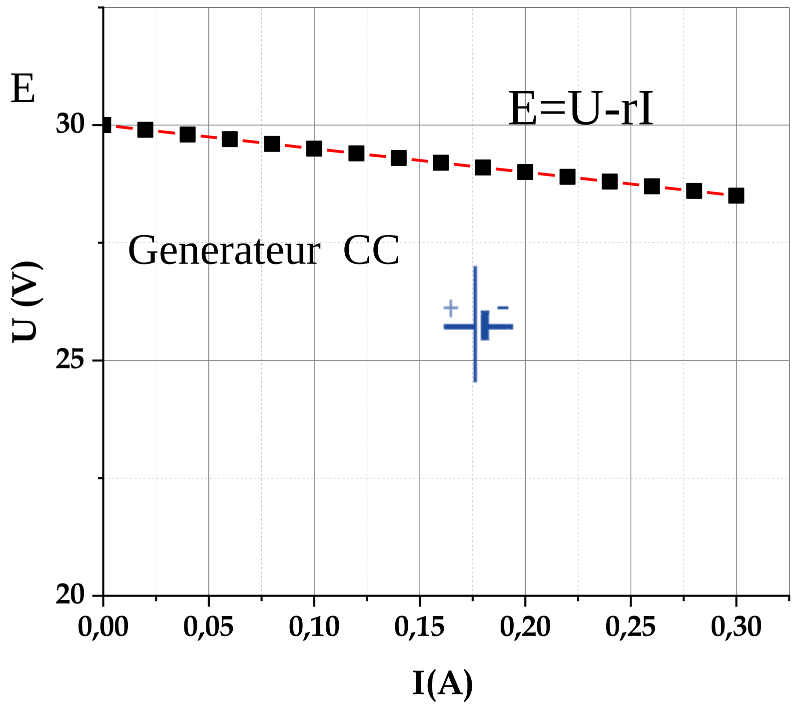


Figure 4.3. Characteristic of a DC voltage generator with an electromotive force of 30V

5. Use of Characteristic Curves: Operating Point

Using characteristic curves to determine the operating point is a key concept in electronics and electrical engineering. The operating point is the precise point on the curve where the component operates under normal circuit conditions. Here is how it is used:

• **Operating Point Analysis**: By using a characteristic curve, you can identify the point where the voltage and current are balanced for a given component. This allows you to understand how the component behaves in a specific circuit.

• **Circuit Optimization**: Knowing the operating point of a component allows you to design or optimize an electrical or electronic circuit to ensure correct and efficient operation. This includes selecting appropriate resistor values, supply voltages, etc.

• **Finding the Power Dissipated**: Knowing the operating point allows you to calculate the power dissipated by the component, which is essential to ensure it does not overheat and remains stable.
• Safety and Reliability Analysis: The operating point is critical for evaluating the safety and reliability of electronic components, preventing overload or overheating conditions.
• **Sizing of Components**: During circuit design, the operating point is crucial for correctly sizing

components (such as resistors and transistors) to ensure they operate within their safe and proper ranges.

• **Failure Analysis**: By monitoring the operating point over time, you can detect unwanted shifts in component behavior, which may indicate an imminent failure.

In summary, using characteristic curves to determine the operating point is essential for designing, optimizing, and maintaining efficient and reliable electrical and electronic circuits. It ensures components operate within specified limits and the overall circuit behaves as expected.

Example:

An 18V – 5W lamp is connected to the terminals of a battery with an electromotive force E = 15V and an internal resistance r = 5 Ω. We plot on the same graph the characteristic of the battery (whose equation is U = -5I + 15) and that of the lamp. The intersection of the two curves gives the operating point: (190 mA – 11 V).

The power dissipated during normal operation is: P = U × I = 2.09 W.

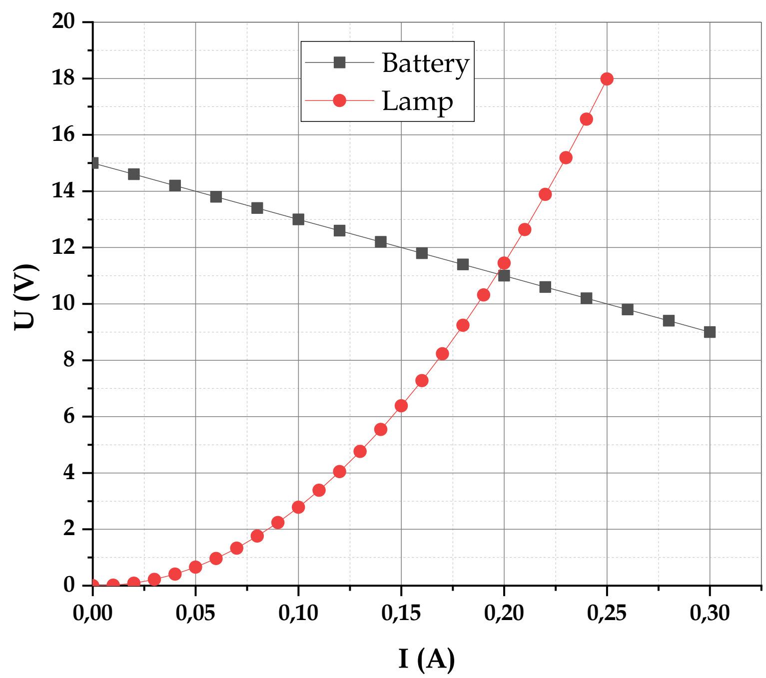
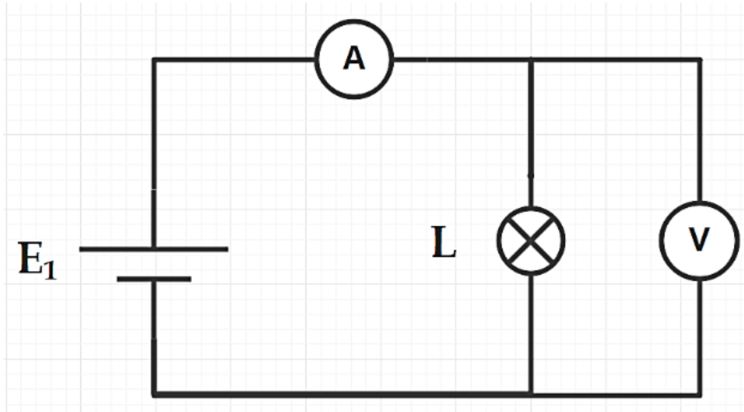


Figure 4.4. Operating point of a lamp

Practical Part

1.Operating Point of an Incandescent Lamp: (12V, 3W)

In this section, we aim to plot the characteristic curve of an incandescent lamp. Lamp Characteristic U = f(I):



Consider the circuit configuration provided by the instructor.

• Measure the cold resistance of the lamp using a multimeter, then set up the circuit.

• Fill in the table below by varying the voltage across the lamp.

At what voltage value does the glow of the lamp become visible? ………………………………...

U (V)	0	1	2	3	4	5	6	7	8	9	10
I (mA)											

• Plot the characteristic curve of the lamp on graph paper (or software) and determine its equation using the same polynomial model discussed in the theoretical section.

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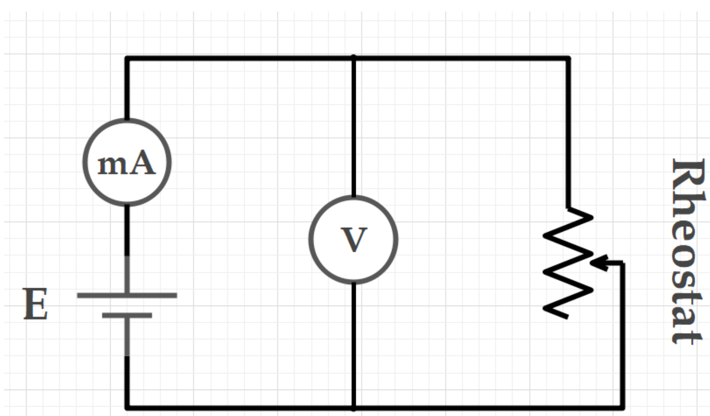
• Deduce the equation for the variation of resistance as a function of the current and plot it on the same graph.

3. Generator Characteristic

Consider the generator circuit configuration.



• Set the voltage displayed on the multimeter V at the beginning of the experiment. to 10

• Fill in the table below by varying the load resistance R:

I (mA)	5	10	20	50	100	150	200
U (V)							

• Plot the generator's characteristic curve U = f(I) on the same graph paper and deduce its equation by applying a linear model.

4. The Operating Point

• Graphically determine the operating point of the circuit and deduce the total power dissipated.

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Experiment No. 5: Network Analysis Theorems

1. Introduction

The study of electrical circuits is a fundamental pillar in the field of electrical engineering, providing the necessary foundations for understanding and solving complex electrical systems. In this context, several theorems prove indispensable for simplifying and analyzing these circuits, including the Superposition Theorem, Thévenin's Theorem, Norton's Theorem, Thévenin-Norton Equivalence, and Millman's Theorem. These theorems represent powerful tools to efficiently approach a variety of electrical problems. This lab manual aims to deepen the understanding of these fundamental concepts and develop the skills required for their application. During this practical work, we will explore the principles of superposition to decompose the effects of independent sources, study the simplification of circuits using Thévenin's and Norton's Theorems, examine the equivalence between these two forms, and apply Millman's Theorem to solve multi-source circuits.

2. Objectives

- **Mastery of Theorems:** Familiarize students with the Superposition, Thévenin, Thévenin-Norton Equivalence, and Millman Theorems.
- **Circuit Simplification:** Learn how to simplify circuits using Thévenin's and Norton's Theorems.
- **Solving Multi-Source Circuits:** Apply Millman's Theorem to solve circuits containing multiple sources.
- **Enhancing Analytical Skills:** Strengthen students' skills in electrical circuit analysis.
- **Ability to Solve Concrete Problems:** Develop the capacity to solve practical problems related to electrical engineering.

3. Materials Used

- One DC power supply with three outputs.
- One digital multimeter.
- Breadboard, banana patch cords, and multimeter probes.
- Six (06) resistors**:** $R_1 = 10\ \Omega$; $R_2 = 100\ \Omega$; $R_3 = 330\ \Omega$; $R_4 = 1\ k\Omega$; $R_5 = 2.2\ k\Omega$; $R_6 = 3.3\ k\Omega$.

Theoretical Part

1. Superposition Theorem

Reminder

The superposition theorem simplifies the analysis of complex circuits by allowing each source to be treated independently. Here is how the superposition theorem works for electrical circuits:

- **Analyze each source individually:** To apply the superposition theorem, start by turning off (setting to zero) or short-circuiting all sources except one. This means you analyze the circuit one source at a time.
- **Calculate the effects of each source:** For each active source, calculate the currents and voltages in the circuit as if that source were the only active one. This means you treat the circuit in the usual way using Kirchhoff's laws and Ohm's law to determine currents and voltages.
- **Repeat for each source:** Repeat this process for each active source, ensuring that all other sources are turned off at each step.
- **Sum the individual effects:** Once you have calculated the effects of each source, you can add them together to obtain the final value of the voltage or current at a given node. This amounts to vectorially/algebraically adding the effects of each source, as voltage and current are directional quantities.

Application

Consider the circuit illustrated in Figure 5.1, which is powered by three independent sources. Calculate the currents I_1, I_4, and I_6 flowing through R_1, R_4, and R_6 by applying the superposition theorem.

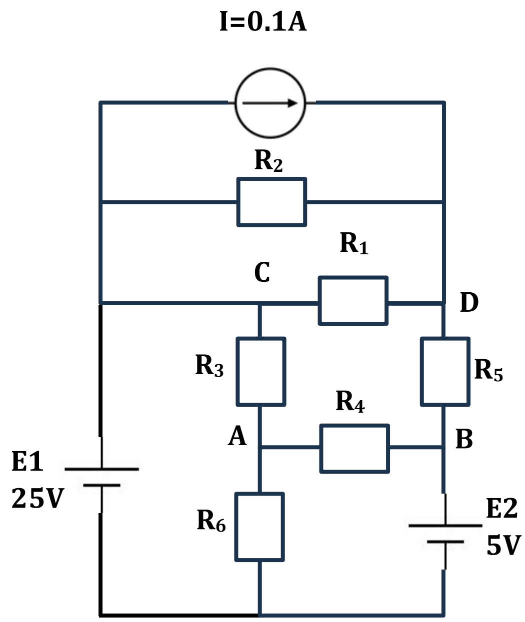


Figure 5.1

2. Thévenin's Theorem

Reminder

Any linear active circuit, viewed from two points A and B, can be replaced by an equivalent Thévenin circuit consisting of a voltage source in series with a resistor. The voltage source is the open-circuit voltage between points A and B, and the resistance is the equivalent resistance seen between these points when all active independent sources in the circuit are deactivated (voltage sources replaced by short circuits).

- **Identify the load:** Identify the specific load for which you want to analyze the voltage or current. This allows you to isolate the rest of the complex circuit across two points A and B that you wish to simplify.
- **Disconnect the load:** Isolate the load from the rest of the circuit by opening the connections or removing the load between points A and B.
- **Calculate the open-circuit voltage (E_{th}) between points A and B:** Calculate the voltage between these points when the load is removed.
- **Calculate the Thévenin resistance (R_{th}):** Calculate the equivalent resistance seen from the load terminals. To do this, turn off all independent voltage and current sources in the circuit, then calculate the equivalent resistance looking into terminals A and B.
- **Represent the Thévenin equivalent circuit:** Use the calculated values to construct the Thévenin circuit: a voltage source E_{th} in series with a resistor R_{th}.
- **Reconnect the load and perform the final calculations:** Reconnect the load to the Thévenin equivalent circuit. You can now easily analyze the simplified circuit using basic electrical laws (such as Ohm's law, voltage divider rule, etc.) to determine the current or voltage across the load.

Application

Consider the circuit illustrated in Figure 5.1. Calculate the currents I_1, I_4, and I_6 flowing through R_1, R_4, and R_6 by applying Thévenin's theorem.

3. Norton's Theorem

Reminder

Norton's theorem is an analysis principle similar to Thévenin's theorem, used to simplify the analysis of complex networks. It focuses on transforming a complex circuit into a simpler equivalent circuit composed of an ideal current source in parallel with a resistor.

1. Identify the load.

2. Disconnect the load.

3. Calculate the short-circuit current (I_N) between terminals A and B when those terminals are directly shorted.

4. Calculate the equivalent resistance, denoted as R_N, between terminals A and B after independent sources have been turned off.

5. Construct the Norton equivalent circuit by placing an ideal current source of value I_N in parallel with a resistor of value R_N between terminals A and B.

6. Reconnect the load and perform the necessary calculations.

Application

Consider the circuit illustrated in Figure 5.1. Calculate the currents I_1, I_4, and I_6 flowing through R_1, R_4, and R_6 by applying Norton's theorem.

4. Millman's Theorem

Reminder:

Millman's theorem is stated as follows:

To solve a network of parallel branches containing resistors and voltage or current sources, the branch voltages can be considered weighted by the reciprocal of their respective resistance. We then calculate the sum of these products and divide it by the sum of the reciprocals of the resistances. Mathematically, this translates as follows: Suppose you have a network of n parallel branches with resistors denoted R_1, R_2, ..., R_n, and corresponding voltages E_1, E_2, ..., E_n across these branches, and that you also have parallel voltage or current sources (Figure 5.2).

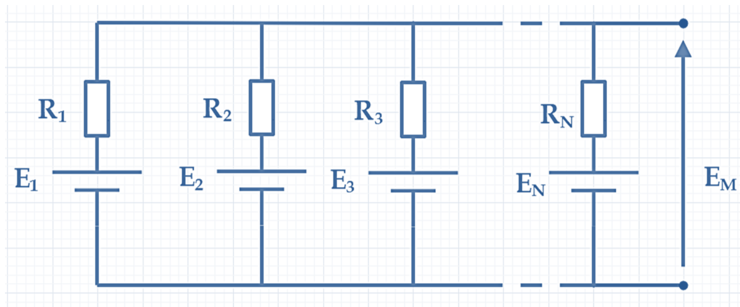


Figure 5.2

The voltage U_M at the common node can be calculated as follows:

$$E_M = \frac{\sum_{i=1}^{n}\frac{E_i}{R_i}}{\sum_{i=1}^{n}\frac{1}{R_i}} = \frac{\pm\frac{E_1}{R_1}\pm\frac{E_2}{R_2}\pm\ldots\pm\frac{E_n}{R_n}}{\frac{1}{R_1}+\frac{1}{R_2}+\ldots+\frac{1}{R_n}}$$

- **The sign of 'E'** in Millman's formula depends on the direction of the chosen voltage E_M; that is, it is positive if they have the same direction and negative otherwise.
- Millman's theorem can be applied if the electromotive force of a voltage source in a branch is zero.
- A branch with a voltage source and zero resistance must not be included in the Millman's theorem calculation.
- Just as the quantity $\frac{E_i}{R_i}$ corresponds to the current, a branch with a current source must be included directly in the Millman's theorem calculation. $\left(\frac{E_1}{R_1}\pm\frac{E_2}{R_2}\pm I_1\pm\ldots\right)$
- Millman's formula can be written in terms of conductance's as follows: $E_M = \frac{\sum_{i=1}^{n} G_i E_i}{\sum_{i=1}^{n} G_i}$

Application

Consider the circuit illustrated in Figure 5.3. Calculate the voltages U_{BC} and U_{AC} across the loads R and R_5 using Millman's theorem by following these steps:

1. Calculate the voltage U_{AB} using Millman's theorem.
2. Simplify the circuit between points A and B using the Millman parameters (V_M and R_M).
3. Deduce the two voltages U_{BC} and U_{AC}.

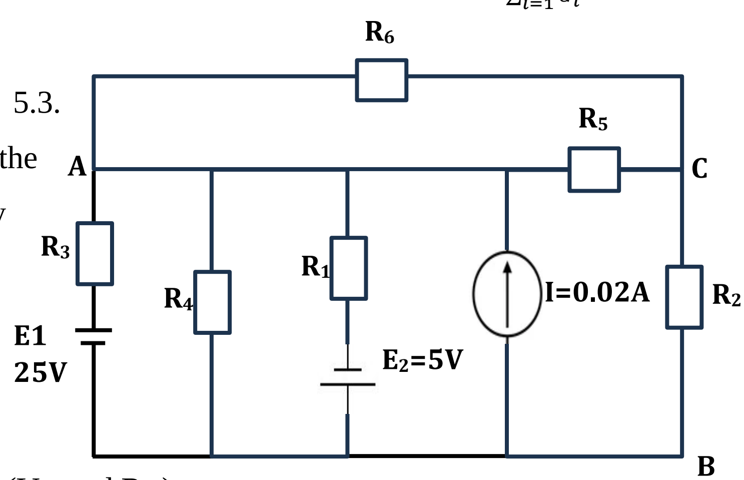


Figure 5.3

Practical Part

Consider the schematic diagram presented in Figure 5.4. The objective is to calculate the current I flowing through each load R_1, R_4 and R_6 by applying the Superposition, Thévenin, and Norton theorems.

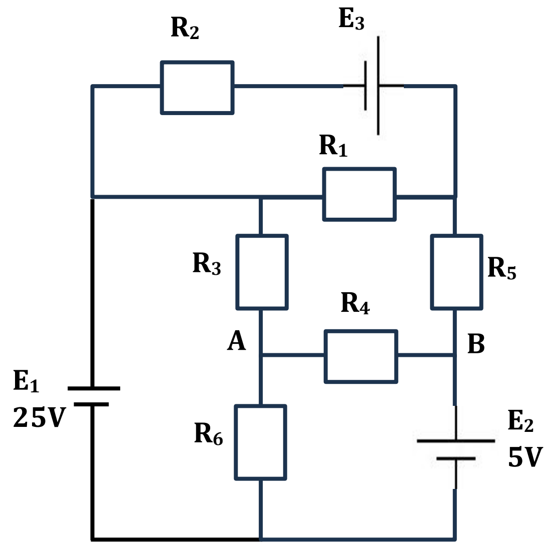


Figure 5.4

1.Prove the equivalence of the diagrams in Figures 5.1 and 5.4, by deducing the value of E_3. ....

....

2. Assemble the circuit illustrated in Figure 5.4.

3. Measure, using a multimeter, the voltage applied across each resistor, by filling in the following table :

Load	R_1	R_4	R_6
Measured Voltage (V)			
Deduced Current I_R (mA)			

Experimental Verification of Superposition Theorem:

1. Apply the superposition theorem for each resistor. Summarize the results in the following table:

Note: Note that the currents I', I", and I'" mentioned in the table represent the individual effects of each source (E_1, E_2, and E_3). For example, I' corresponds to the current obtained if source E1 were the only active source.

Load	R_1	R_4	R_6
Measured I_R (mA)			
Measured I' (mA) (Only E_1 Active)			
Measured I'' (mA) (Only E_2 Active)			
Measured I''' (mA) (Only E_3 Active)			
Calculated I_R (mA) (From Theory)			

Question: Compare the experimental load currents for R_1, R_4, and R_6 with the theoretical values calculated.

2. Experimental Verification of Thévenin's Theorem

Using the same circuit setup from Figure 5.1.

1: Apply Thévenin's theorem to each load resistor by disconnecting it, measuring the open-circuit voltage Vth and equivalent resistance R_{th}, and record the data below:

Load	R_1	R_4	R_6
Voltage V_{th} (V)			
Resistance R_{th} (Ω)			

Sketch the simplified Thévenin equivalent circuit for each load configuration and calculate the expected load current. Complete the summary table:

Load	R_1	R_4	R_6
Measured I_R (mA)			
Measured V_{th} (V)			
Measured R_{th} (Ω)			
Simplified Thévenin Circuit Diagram			
Calculated I_R (mA)			

Question: Compare the experimental load currents for R_1, R_4, and R_6 with the theoretical values calculated.

3. Experimental Verification of Norton's Theorem

Using the same circuit configuration from Figure 5.1: Apply Norton's theorem to measure the short-circuit Norton current I_N for each load, and deduce the Norton resistance R_N. Complete the table below:

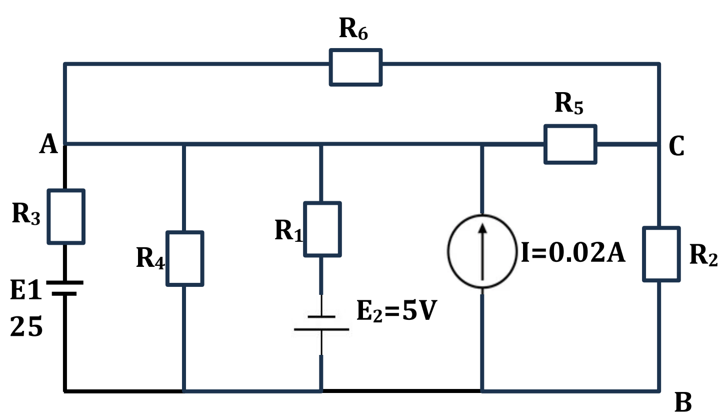
Load	R_1	R_4	R_6
Measured I_R (mA)			
Deduced R_N (Ω)			
Deduced I_N (mA)			
Measured I_N (mA)			
Simplified Norton Circuit Diagram			
Calculated I_R (mA)			

Note: *The deduced resistance R_N and deduced current I_N columns refer to values derived via the Thévenin-Norton source transformation equivalence ($R_N = R_{th}$ and $I_N = V_{th} / R_{th}$).*

Question: Compare the experimental results for loads R_1, R_4, and R_6 with your theoretical calculations.

4. Experimental Verification of Millman's Theorem

Consider the circuit illustrated in Figure 5.3. The objective is to calculate the voltages U_{BC} et U_{AC} across the loads R et R_5 by applying Millman's theorem.



1.Measure the voltages U_{AB}, U_{BC} and U_{AC} and compare them with those calculated in the theoretical part.

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Experiment No. 6: Calculations in Complex Model - RLC Circuit Resonance

1. Introduction:

In the field of electrical engineering, the study of circuits in single-phase sinusoidal steady-state is of paramount importance, representing a key model for describing the variation of alternating currents (AC) in electrical systems. This steady-state, characterized by a periodic sinusoidal wave, constitutes the foundation of many industrial and domestic applications and serves as a basis for modern methods of analysis and design in electrical engineering.

Complex representation stands out as an essential approach for the study of sinusoidal quantities. By using complex numbers, it simplifies calculations related to sinusoidal signals and allows for a more intuitive understanding of electrical phenomena. In particular, the complex exponential form offers a compact and powerful modeling tool, widely used to analyze the impedances of elementary two-terminal components such as resistors, ideal inductors, and capacitors.

Within the framework of this practical work (lab), we explore the fundamental principles of analyzing circuits in sinusoidal steady-state using the complex model. This includes the application of fundamental laws, such as Kirchhoff's laws, and the study of the principles of grouping passive two-terminal components, while emphasizing the concepts of power in AC steady-state.

2. Objectives

- **Visualization of Sinusoidal Quantities:** Learn to observe sinusoidal quantities on an oscilloscope and extract essential characteristics, namely the waveform, frequency, amplitude, and phase.
- **Introduction to Complex Models:** Understand the use of complex numbers to represent sinusoidal quantities, and master their application in the analysis and solving of AC circuits.
- **Power Analysis in Sinusoidal Steady-State:** Define and interpret the different types of power (instantaneous, average, active, reactive, apparent) as well as the power factor, linking them to complex model quantities.
- **Application of Boucherot's Theorem:** Discover and apply Boucherot's theorem for power analysis in AC circuits, highlighting its effectiveness and limits in a practical setting.

- ❖ **Practical Understanding of Resonance Phenomena:** Study voltage resonance across the resistor and current resonance in the series RLC circuit.

3. **Materials Used:**

- Low Frequency Generator (LFG) / Function Generator.
- A digital multimeter.
- Circuit Components: Resistors (100 Ω; 330 Ω); Capacitor (0.1μF), Inductor (33mH).
- Accessories: Breadboard and connection cables (banana-to-banana leads and BNC/banana).

Theoretical Part

1 Definition of Sinusoidal Quantities:

A sinusoidal quantity is an electrical quantity (voltage or current) that varies periodically according to a sine waveform. This regular variation is characterized by a constant frequency (f), expressed in hertz (Hz), and an amplitude (Xm) which represents the maximum value of the quantity.

Algebraic form:

$x(t) = X_m \, cos(\omega t + \varphi)$

X_m: amplitude

ω : angular frequency

φ : initial phase (t=0).

$(\omega t + \varphi)$: instantaneous phaseo

$f = \frac{1}{T} \begin{cases} f: frequency(Hz) \\ T: periode(s) \end{cases}$

$\omega = \frac{2\pi}{T} = 2\pi f$

$X_{eff} = \frac{X_m}{\sqrt{2}}$ (X_{eff} : RMS value)

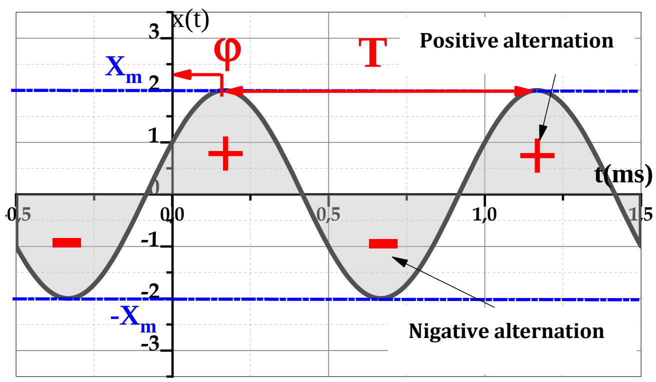


Figure 6.1. Graphical representation of a sinusoidal signal $x(t) = 2\,\boldsymbol{cos}\left(4\pi t - \frac{\pi}{3}\right)$

Note: The phase shift is the phase difference between two synchronous sinusoidal quantities (of the same frequency). It can be given by: $\Delta\varphi = \omega\Delta t = 2\pi\frac{\Delta t}{T}$with $\Delta\varphi \in \,]-\pi; \pi]$

2. Representations of sinusoidal quantities Both approaches, vector representation and complex representation, are essential tools for adding sinusoidal signals and understanding their characteristics.

2.1 Vector representation (Fresnel method) Vector representation, also known as the Fresnel method, is a graphical approach that uses vectors to graphically represent the amplitude and phase of sinusoidal signals. In particular, this method makes it easier to add sinusoidal quantities of the same frequency.

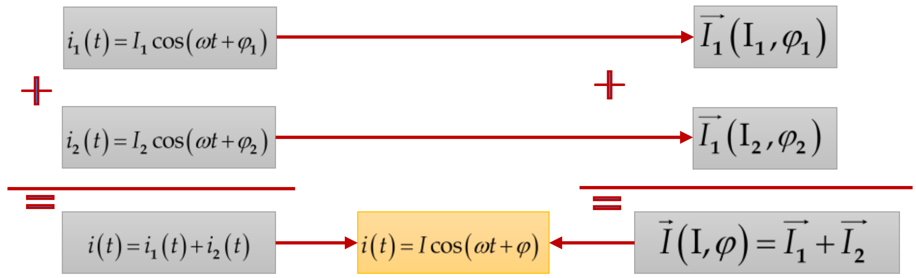


Figure 6.2. Diagram summarizing the Fresnel method

Let us consider two sinusoidal currents: $\begin{cases} i_1(t) = I_1\, cos(\omega t + \varphi_1) \\ i_2(t) = I_2\, cos(\omega t + \varphi_2) \end{cases}$

The sum of the two currents is: To find $i(t)$, we can proceed graphically: $i(t) = i_1(t) + i_2(t)$

- Consider a vector denoted $\vec{\boldsymbol{I_1}}$, of magnitude I_1, rotating in the (xOy) plane at an angular velocity ω, and whose angle with the (Ox) axis at an instant t is equal to $(\boldsymbol{\omega t} + \boldsymbol{\varphi_1})$. We similarly define a vector $\vec{\boldsymbol{I_2}}$ The projections onto (Ox) of the vectors $\vec{\boldsymbol{I_1}}$ and $\vec{\boldsymbol{I_2}}$ are equal to the currents i_1 and i_2, respectively.

The sum of the two currents i(t) is the projection of the sum vector: $i(t) = i_1(t) + i_2(t) \rightarrow \vec{I} = \vec{I_1} + \vec{I_2}$

$$i(t) = I_m \cos(\omega t + \varphi) \qquad où \qquad I_m = |\vec{I}| = |\vec{I_1} + \vec{I_2}|$$

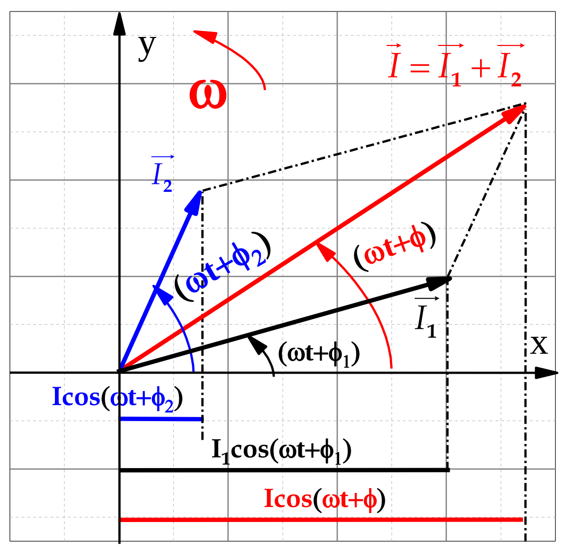


Figure 6.3 : Addition of two sinusoidal currents, $i_1(t)$ and $i_2(t)$, of the same frequency, using the Fresnel method

2.2 Complex representation

Complex representation uses complex numbers to represent quantities, facilitating the mathematical calculations associated with sinusoidal signals.

- For any given instant, associate complex quantities corresponding to
$$u_1(t) + u_2(t) = U_1\, cos(\omega t + \varphi_1) + U_2\, cos(\omega t + \varphi_2)$$
- Deduce the complex quantity: $\underline{U} = \underline{U_1} + \underline{U_2} = Ue^{j\varphi}$
- Deduce the amplitude of U (the modulus of $\underline{U}$) and the phase (the argument of $\underline{U}$). We do the same for a difference.

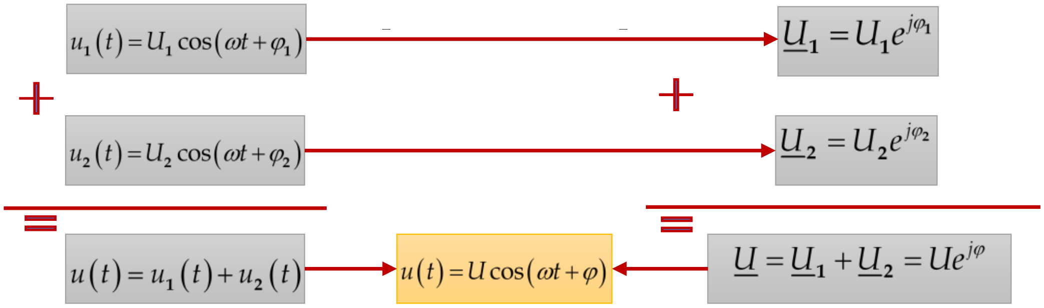


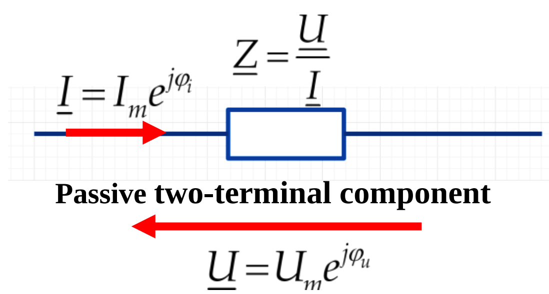
Figure 6.4. Diagram summarizing the complex method

3. Complex model of a circuit in sinusoidal steady-state :

The complex model of a circuit in sinusoidal steady-state relies on the complex representation of sinusoidal quantities, namely the supply voltage (e(t)) for an active two-terminal component and the current (i(t)) as well as the voltage (u(t)) for a passive two-terminal component.

3.1 Complex impedances:

In the complex model, each linear passive two-terminal component is characterized by two quantities, the current (i(t)) and the voltage (u(t)), defined by their respective complex forms as follows:



$$\begin{cases} u(t) = U_m \cos(\omega t + \varphi_u) \longrightarrow \underline{U} = U_m e^{j\varphi_u} \\ i(t) = I_m \cos(\omega t + \varphi_i) \longrightarrow \underline{I} = I_m e^{j\varphi_i} \end{cases}$$

Therefore, based on Ohm's law, we can define the complex impedance $(\underline{Z})$ of a two-terminal component in a sinusoidal steady-state circuit:

$$\boxed{\underline{Z} = \frac{\underline{U}}{\underline{I}} = \frac{U_m e^{j\varphi_u}}{I_m e^{j\varphi_i}} = \frac{U_m}{I_m} e^{j(\varphi_u - \varphi_i)}}$$

- Z is the modulus of $\underline{Z}$, representing the impedance magnitude (real impedance).

- $(\varphi_u - \varphi_i)$ or φ is the argument of $\underline{Z}$, representing the phase shift of the voltage with respect to the current.

- U and I represent the RMS values of the voltage and current, respectively.

Thus, complex impedance is a complex number defined by its modulus and its argument, as follows:

$$\boxed{\underline{Z}:\begin{cases}|\underline{Z}| = Z = \dfrac{U_m}{I_m} = \dfrac{U\sqrt{2}}{I\sqrt{2}} = \dfrac{U}{I} \\ arg(\underline{Z}) = (\varphi_u - \varphi_i) = \varphi[2\pi]\end{cases}}$$

It can be written $\underline{Z}$ in algebraic form as follows: $\underline{Z} = \frac{U}{I}cos(\varphi) + j\frac{U}{I}sin(\varphi)$

Therefore, the complex impedance is represented by the notation: $\boxed{\underline{Z} = R + jX}$

Where:

$R = Re(\underline{Z}) = \frac{U}{I}cos(\varphi)$ represents the resistance of the two-terminal component (real part of the impedance)

$X = Im(\underline{Z}) = \frac{U}{I}sin(\varphi)$ represents the reactance of the two-terminal component (imaginary part of the impedance)

3.2. Complex impedances of R, L, and C two-terminal components:

3.2.1. Fundamental Theory of Complex Impedance:

In alternating current (AC) circuit analysis, the concept of complex impedance (Z) generalizes Ohm's law to include time-varying sinusoidal signals. Instead of treating resistance as a simple real number, complex numbers are utilized to account for both the magnitude scaling and the phase shifting introduced by reactive components. A complex impedance is mathematically expressed as:

$$\mathbf{Z = R + jX}$$

R: Resistance (the real part, which dissipates active power as heat).

X: Reactance (the imaginary part, which stores and releases energy in electric or magnetic fields).

j: The imaginary unit, defined by $j^2 = -1$.

ω: Angular frequency ($\omega = 2\pi f$, expressed in radians per second), where f is the frequency in Hertz (Hz).

3.2.2. Element-by-Element Impedance Characteristics:

a. Pure Resistor (R):

A pure resistor limits current strictly through collisions of charge carriers. It does not store energy, meaning that the alternating voltage and alternating current waveforms remain perfectly in phase with each other, resulting in a 0° phase shift.

- **Complex Impedance:** $Z_R = R$
- **Magnitude:** $|Z_R| = R$
- **Phase Angle:** $\theta = 0°$

b. Pure Inductor (L):

An inductor opposes changes in electric current by storing energy in a localized magnetic field. In a purely inductive component, the voltage waveform leads the current waveform by exactly 90° (π/2 radians).

- **Complex Impedance:** $Z_L = j\omega L = j2\pi fL$
- **Inductive Reactance (X_L):** $X_L = \omega L$ (increases linearly with operating frequency)
- **Magnitude:** $|Z_L| = \omega L$
- **Phase Angle:** $\theta = +90°$

c. Pure Capacitor (C):

A capacitor opposes transitions in electric voltage by storing energy within an electric field established between its plates. In a purely capacitive component, the voltage waveform lags behind the current waveform by exactly 90° (-π/2 radians).

- **Complex Impedance:** $Z_C = 1 / (j\omega C) = -j / (\omega C) = -j / (2\pi fC)$
- **Capacitive Reactance (XC):** $X_C = 1 / (\omega C)$ (decreases inversely as frequency increases)
- **Magnitude:** $|Z_C| = 1 / (\omega C)$
- **Phase Angle:** $\theta = -90°$

3. Comparative Technical Summary Table

Component	Complex Impedance (Z)	Reactance (X)	DC Behavior (f = 0)	High Freq Behavior (f → ∞)
Resistor (R)	R	0	Unchanged (R)	Unchanged (R)
Inductor (L)	jωL	ωL	Short Circuit (0 Ω)	Open Circuit (∞ Ω)
Capacitor(C)	1 / (jωC)	-1 / (ωC)	Open Circuit (∞ Ω)	Short Circuit (0 Ω)

4. The Impedance Triangle and Vector Synthesis

When passive components are combined in a series topology, their cumulative impedance is mapped geometrically on the complex plane using an impedance triangle. The total resistance sits firmly on the real horizontal axis, whereas the combined net reactance ($X_L - X_C$) populates the vertical imaginary axis.

Total Complex Impedance: $Z_{total} = R + j(X_L - X_C)$

Total Vector Magnitude: $|Z_{total}| = \sqrt{(R^2 + (XL - XC)^2)}$

Phase Angle Formula: $\theta = \tan^{-1}((X_L - X_C) / R)$

4 . Complex Power, Active Power, and Reactive Power :

In order to have a power model related to the complex models of the circuits, a concept of **complex power** $\underline{S}$ is defined as follows:

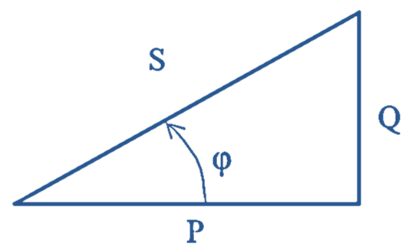
$$\boxed{\underline{S} = \underline{U}.\underline{I}^*} \text{ with: } \begin{cases} \underline{U} = Ue^{j\varphi_u} \\ \underline{I} = Ie^{j\varphi_i} \longrightarrow \underline{I}^* = Ie^{-j\varphi_i} \end{cases}$$

It is easily shown that: $\underline{S} = Ue^{j\varphi_u}Ie^{-j\varphi_i} = U.I.e^{j(\varphi_u - \varphi_i)} = U.I[cos(\varphi_u - \varphi_i) + j\, sin(\varphi_u - \varphi_i)]$

$$\underline{S} = \underbrace{U.I\, cos(\varphi)}_{P} + j\, \underbrace{U.I\, sin(\varphi)}_{Q}$$

Therefore, we can write: $\boxed{\underline{S} = P + jQ}$ avec $\begin{cases} P = U.I\, cos(\varphi) \\ Q = U.I\, sin(\varphi) \end{cases}$

" triangle des puissances"



$P = U.I\, cos(\varphi)$, known as **active power** (expressed in Watts, **W**), corresponds to the average power consumed by the two-terminal component (P=P_{moy}).

$Q = U.I\, sin(\varphi)$, known as **reactive power** (expressed in volt-ampere-reactive, **VAR**), corresponds to the power exchanged between the source and the non-resistive elements of the two-terminal component (inductive or capacitive), without any net average power consumption.

$$S^2 = P^2 + Q^2$$

$$\tan\varphi = \frac{Q}{P}$$

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

$S = |\underline{S}| = \sqrt{p^2 + Q^2} = U.I$, known as **apparent power** (expressed in volt-amperes, **VA**), represents the total power in the circuit, combining both the active power (P) and the reactive power (Q).

$F = cos(\varphi) = \frac{P}{S}$, known as the **power factor**, indicates the efficiency with which electrical energy is converted into useful work.

4.1. Relations between Impedance and Power

We have : $\underline{Z} = R + jX avec \begin{cases} R = \frac{U}{I} cos(\varphi) \\ X = \frac{U}{I} sin(\varphi) \end{cases}$ and $\underline{S} = P + jQ avec \begin{cases} P = U.I\, cos(\varphi) \\ Q = U.I\, sin(\varphi) \end{cases}$

Therefore, we can write: $\begin{cases} P = \frac{U}{I} I^2 cos(\varphi) = RI^2 \\ Q = \frac{U}{I} I^2 sin(\varphi) = XI^2 \end{cases}$

$$\text{and } S = \sqrt{p^2 + Q^2} = \sqrt{I^4(R^2 + X^2)} = I^2\sqrt{(R^2 + X^2)} = Z.I^2$$

- **Boucherot's Theorem**

The total active and reactive power absorbed by a combination of two-terminal components are respectively equal to the sum of the active and reactive powers absorbed by each individual element of the group: $\boxed{P_{tot} = \sum_{i=1}^{n} P_i = P_1 + P_2 + \ldots + P_n}$ and $\boxed{Q_{tot} = \sum_{i=1}^{n} Q_i = Q_1 + Q_2 + \ldots + Q_n}$

Note: Boucherot's theorem is **not** valid for the apparent power S.

However, the expressions for the total complex power $\underline{S}$ and the total apparent power S can be deduced using the total active and reactive powers as follows:

$$S_{tot} = \sqrt{{P_{tot}}^2 + {Q_{tot}}^2} \qquad \underline{S}_{tot} = P_{tot} + jQ_{tot} = \underline{S}_1 + \underline{S}_2 + \ldots + \underline{S}_n$$

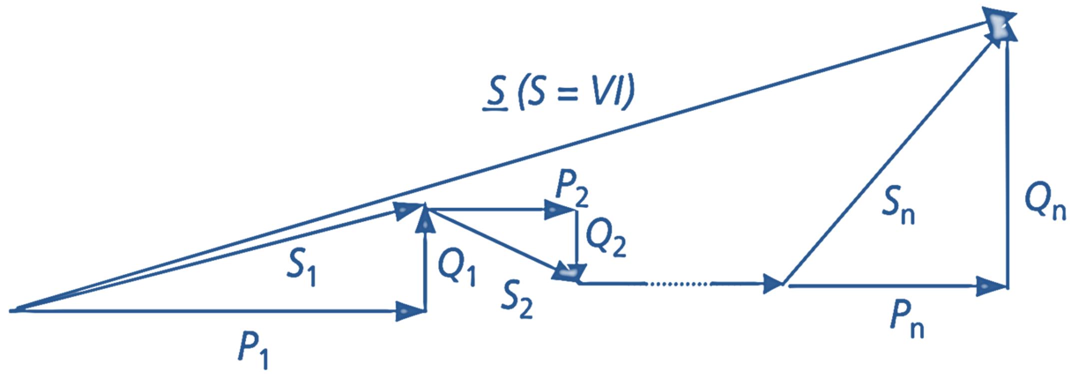


Figure 6.5 Boucherot's theorem and power triangles.

- **Series RLC Circuit:**

A series RLC circuit is a foundational electrical configuration consisting of a resistor (R), an inductor (L), and a capacitor (C) connected sequentially in a single current loop. Driven by a sinusoidal alternating voltage source, this circuit is characterized by a single, uniform current i(t) flowing through all components at any given instant (Figure 6.6). According to Kirchhoff's Voltage Law (KVL),

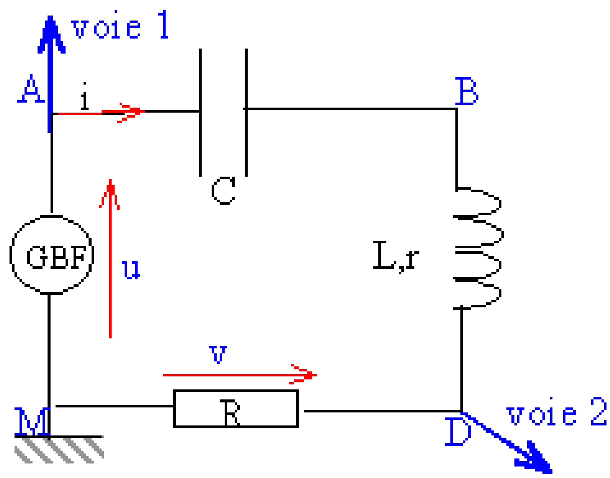


Figure 6.6 : series RLC circuit

6.1. The Complex Model (Magnitude and Argument):

In steady-state sinusoidal analysis, the complex model eliminates the need for tedious time-domain differential equations by mapping time-varying signals into stationary vectors, known as phasors, within the complex plane. The total complex impedance of a series RLC circuit is algebraically expressed as: $\underline{Z} = R + j(L\omega - 1/(C\omega))$.

- **The magnitude** of the impedance, denoted as $Z=|\underline{Z}|= \sqrt{[R^2 + (L\omega - 1/(C\omega))^2]}$, physically represents the total opposition of the circuit to the alternating current. It establishes a direct linear relationship between the voltage and current amplitudes ($U=Z\cdot I$).
- **The argument** (or phase angle) of the impedance, defined as: $\varphi=\arg(\underline{Z})=\arctan([L\omega- 1/(C\omega)]/R)$, represents the exact phase shift of the voltage relative to the current. Depending on the sign of this argument, the circuit behaves either inductively ($\varphi > 0$, where voltage leads current) or capacitively ($\varphi < 0$, where voltage lags behind current).

6.2. Current Resonance (Current and Amplitude):

Current resonance is a remarkable phenomenon that occurs when the supply voltage frequency matches the circuit's natural resonant frequency, defined as $f_0 = 1/(2\pi\sqrt{(LC)})$. At this specific frequency, the inductive and capacitive reactances cancel each other out completely ($L\omega_0 = 1/(C\omega_0)$), reducing the imaginary part of the impedance to zero. Consequently, the total impedance magnitude drops to its absolute minimum value, which is simply the resistance R. Under a constant input voltage amplitude, the circuit current reacts dynamically, maximizing its amplitude to $I_{max}=U/R$. Plotting the current amplitude against frequency yields a distinct resonance curve centered at f_0. The sharpness and selectivity of this peak are determined by the circuit's Quality Factor (Q): a lower resistance R results in a highly acute, narrow, and selective resonance peak.

Practical Part

Problem I : Complex Model Calculations :

Consider the setup illustrated in Figure 6.7. The objective is to calculate all the complex quantities for the various impedances in this circuit using two methods: theoretical and experimental.

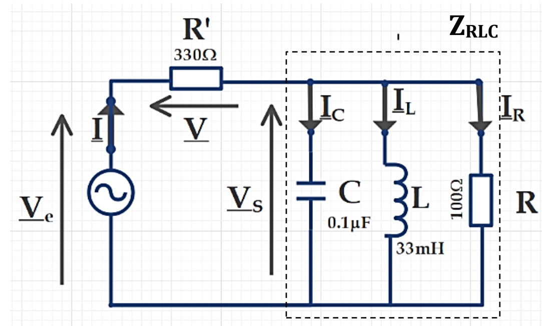


Figure 6.7

- **Experimental Measurements:**

1. **Set up the circuit** as illustrated in the attached figure, adjusting the function generator frequency to **5 kHz**.
2. **Use a multimeter** in AC mode to adjust the input voltage as follows: $V_e(t) = 3\sqrt{2}\, sin(\omega t)$

   N.B.: In AC (alternating current) mode, the voltmeter measures the root-mean-square (**RMS**) value of the voltage.
3. **Complete the following table:**

	R'	**R**	**L**	**C**
Measured RMS voltage (V)	**V=…………….**	**V_s=…………………..**		
Calculated impedance (kΩ)	**$Z_{R'}$=………….**	**Z_R=…………..**	**Z_L= …………..**	**Z_C= …………..**
Deduced RMS current (mA)	**I=…………….**	**I_R=…………….**	**I_L=…………….**	**I_C=…………….**
Measured RMS current (mA)	**I=…………….**	**I_R=…………….**	**I_L=…………….**	**I_C=…………….**
Active power P (W)	…………….	…………….	…………….	…………….
Reactive power Q (VAR)	…………….	…………….	…………….	…………….
Apparent power S (VA)	…………….	…………….	…………….	…………….

4. Deduce the total equivalent impedance Z and Z_{RLC} of the parallel RLC section..
……
……
……………………………………. .

5. By applying Boucherot's theorem, deduce the power factor ($cos\,\varphi$) of the circuit

$$\begin{cases} P_{tot} = \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ Q_{tot} = \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ S_{tot} = \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \end{cases}$$

$cos\,\varphi =$

....

6. **Use a dual-channel oscilloscope** to measure the phase shift of $V_s(t)$ **with respect to** $V_e(t)$, and then of $V(t)$ **with respect to** $V_e(t)$, indicating which one is leading.

— $V_s(t)$ **with respect to** $V_e(t)$: ΔT=..................=> $\Delta\varphi$=...

....

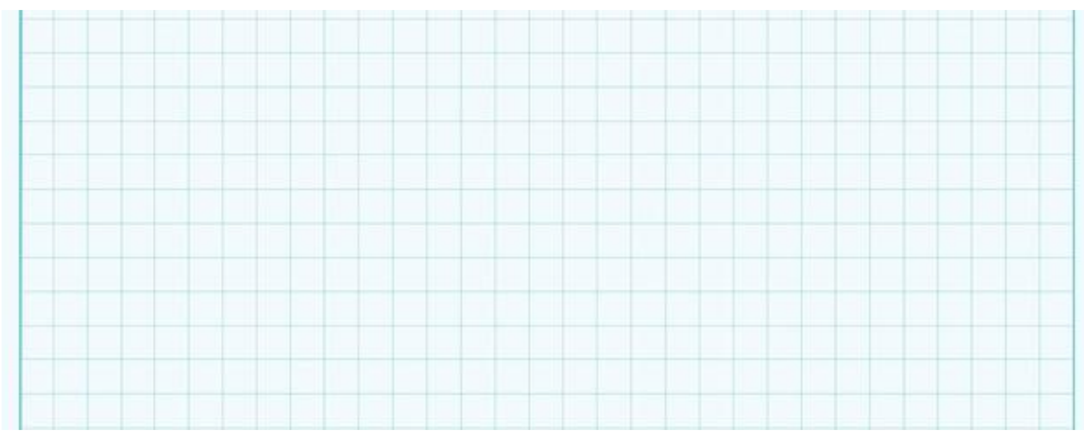
— $V(t)$ **with respect to** $V_e(t)$: $\Delta T'$=..................=> $\Delta\varphi$=...

....

1. Give the polar form of the complex voltages $\underline{V}_e$, $\underline{V}$ and $\underline{V}_s$

$\underline{V}_e$=................................	**$\underline{V}$=**................................	**$\underline{V}_s$=**..............................

- Represent the three voltages using the Fresnel diagram method:



7. Deduce the polar forms of the complex currents $\underline{I}_e$, $\underline{I}_R$, $\underline{I}_L$ and $\underline{I}_C$

$\underline{I}_e$ =..................	**$\underline{I}_R$ =**..................	**$\underline{I}_L$ =**......................	**$\underline{I}_C$=**......................

- Represent the four currents using the Fresnel diagram method:

Theoretical Verification:

N.B.: All complex values of the quantities listed below must be presented in exponential or polar form.

1. Calculate the complex impedance $\underline{Z}_{RLC}$ and the total complex impedance $\underline{Z}$ of the circuit, then deduce the type of circuit and and cos φ

………

………

………

………

2. Deduce the complex value of the input current $\underline{I}_e$.

………

………

………

3. Deduce the complex values of the voltages tensions $\underline{V}$ and $\underline{V}_s$.

………

………

………

4. Knowing that the complex apparent power is defined by: $\underline{S} = \underline{V} \times \underline{I} *= \underline{Z} \times I^2$

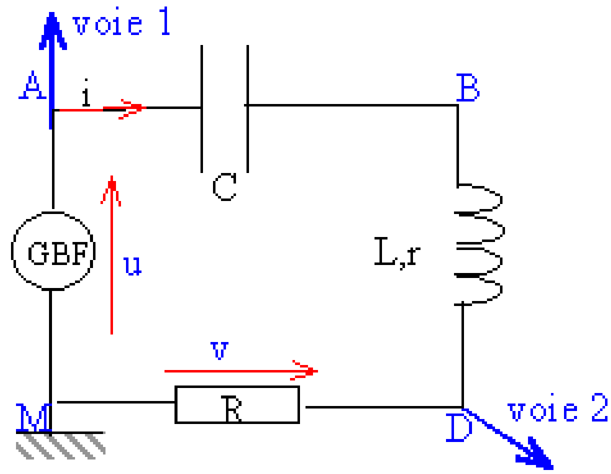
Calculate the complex apparent power of the circuit, deducing the total active and reactive powers.

………

………

……
……

Problem II: Series RLC Circuit Resonance



Consider a circuit comprising an inductor L, a resistor R, and a capacitor C connected in series, all powered by a sinusoidal voltage:

$$V_e(t) = 3\sqrt{2}\,sin(\omega t)$$

Given: C = 0.1 μF, R = 100 Ω, and L = 33 mH.

1. Set up the circuit shown in the figure and connect the two oscilloscope channels (Y_1 and Y_2) to visualize $V_e(t)$ and $V_R(t)$
2. Using the oscilloscope, measure the phase shift between $V_e(t)$ and $V_R(t)$ for:

   f_1=2 KHz ⟶ φ_1= ……………………..

   f_2=5 KHz ⟶ φ_2=………………………

   Conclusion:

   ……………………………………………………………………………………………
   ……………………………………………………………………………………………
   …………………………………………………………………………

3. Vary the input frequency starting from 1 KHz until you obtain a zero phase shift between $V_e(t)$ and $V_R(t)$. Note the resonance frequency of the circuit: $f0$ = ………………….
   a) Compare the obtained value with the theoretical value : ……………………

   $$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi\sqrt{LC}} = \ldots\ldots\ldots\ldots\ldots\ldots$$

   b) Measure the resonance current:

   ……………………………………………………………………………………

   Compare it with the theoretical value:

…………………………………………………………………………………………

…………………………………………………………………………………………

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