Practical 2.5
OHM'S LAW FOR DC CIRCUITS

October 25, 2017

1 Introduction

In this practical, we analyze simple electrical circuits that contain batteries and resistors in various combinations. Some circuits contain resistors that can be combined using simple rules. The analysis of more complicated circuits is simplified using Kirchoff rules, which follow from the laws of conservation of energy and conservation of electric charge for isolated systems. Most of the circuits analyzed are assumed to be in steady state, which means that currents in the circuit are constant in magnitude and direction. A current that is constant in direction and not changing with time is called a **direct current (DC)**.

1.1 Electromotive force

As a source of energy for circuits one can use a battery. Because the potential difference at the battery terminals is constant in a particular circuit, the current in the circuit is constant in magnitude and direction and is called direct current. A battery is called either a source of **electromotive force** or, more commonly, a source of **emf**. The emf ε of a battery is the maximum possible voltage the battery can provide between its terminals. You can think of a source of emf as a "charge pump". When an electric potential difference exists between two points, the source moves charges "uphill" from the lower potential to the higher.

We shall generally assume the connecting wires in a circuit have no resistance. The positive terminal of a battery is at a higher potential than the negative terminal. Because a real battery is made of matter, there is resistance to the flow of the charge within the battery. This resistance is called internal resistance r. For an ideal battery with zero internal resistance, the potential difference across the battery (called its terminal voltage) equals its emf.

For a real battery, however, the terminal voltage is not equal to the emf of the battery. To understand why, consider the circuit diagram in Figure 1. The battery is represented by the dashed rectangle containing an ideal, resistance-free emf ε in series with an internal resistance r. A resistor of resistance R is connected across the terminals of the battery. Now imagine moving through the battery from **a** to **d** and measuring the electric potential at various locations. Passing from the negative terminal to the positive terminal, the potential increases by an amount ε. As we move through the resistance r, however, the potential decreases by an amount Ir, where I is the current in the circuit. Therefore, the terminal voltage of the battery $\Delta V = V_d - V_a$ is

$$\Delta V = \varepsilon - Ir. \tag{1}$$

From this expression, notice that ε is equivalent to the open-circuit voltage, that is, the terminal voltage when the current is zero. The emf is the voltage labeled on a battery. The actual potential difference between the terminals of the battery depends on the current in the circuit as described by Equation 1.

Figure 2 is a graphical representation of the changes in electric potential as the circuit is traversed in the clockwise direction. The terminal voltage ΔV must equal to the potential difference across the external resistance R, often called the load resistance. The load resistor might be a simple resistive circuit element as in Figure 1, or it could be the resistance of some electrical device (such as an electric heater, or lightbulb) connected to the battery (or, in case of household devices, to the wall outlet). The resistor represents a load on the battery because the battery must supply energy to operate the device containing the resistance. The potential difference across the load resistance is $\Delta V = IR$. Combining this expression with Equation 1, we see that

$$\varepsilon = IR + Ir. \tag{2}$$

Figure 2 shows a graphical representation of this equation. Solving for the current gives

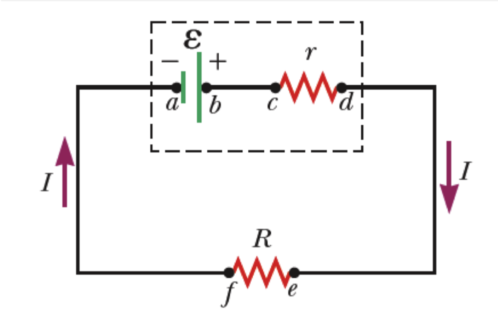

Figure 1: Cirquit diagram of a source of emf ε, of internal resistance r connected to an external resisistor of resistance R.

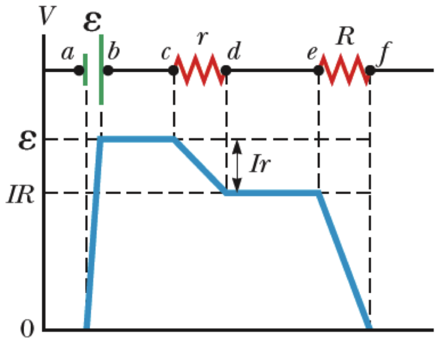

Figure 2: Graphical representation showing how the electric potential changes as the circuit in Fig. 1 is traversed clockwise.

$$I = \frac{\varepsilon}{R + r}. \tag{3}$$

Eq. 3 shows that the current in the simple circuit depends on both the load resistance R external to the battery and the internal resistance r. If R is much greater than r, as it is in many real-world circuits, we can neglect r.

2 Experimental tasks

1. Determine the values of two unknown resistors by using the ammeter and voltmeter method and taking into account the resistance of the measuring devices.
2. Determine the emf and internal resistance of two sources by using Ohm's law.
3. Verify experimentally the applicability of Ohm's law for inhomogeneous electric circuits.
4. Study the distribution of potential in unbranched circuits.

Equipment: digital multimeter, two power supplies BC4-12 as DC power supplies, two resistors (red and green), analog multimeter M2000, voltmeter M2018 or M2017, milliammeter M2020 or M2015, connecting wires.

3 Preparation of protocols

Task 1. Determination of unknown resistance using ammeter-voltmeter based method

In this task a value of uknown resistance is determined in two ways. In the first one (Figure 3(a)), the ammeter measures the total current flowing through the voltmeter and the resistor under study. The voltmeter displays voltage drop across the load resistor only.

In the second case (Figure 3(b)), the voltmeter will show the total voltage drop at the ammeter and resistor, meanwhile the ammeter shows the current through the resistor only.

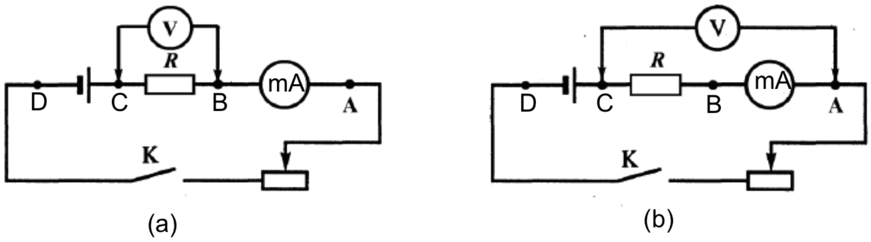

Figure 3:

Draw circuit diagrams in your notebook (Figure 3). Derive formulaes for calculation of uknown resistance R. (Hint! Apply the Ohm law).

Prepare two Tables for recording experimental data and results for the two accessible resistors (as an example, Table 1).

Table 1:

N	I (mA)	V (V)	R_{red} (Ohm)	R_{green} (Ohm)
1				
2				
3				

Calculate and write down the average values of R_{red}, R_{green}, estimate absolute and relative uncertainties for measurement.

Task 2. Determination of emf and an internal resistance of a power supply

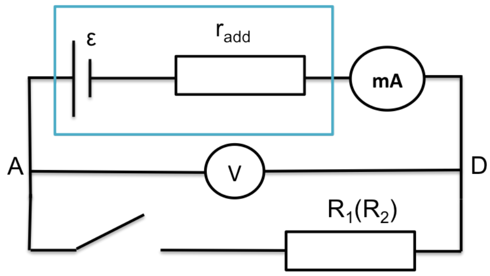

Figure 4:

Schematic diagram is shown in Figure 4. The voltmeter is connected to the points A and D. If the resistance R is considered as an internal resistance of power source ($r = R$), the potential difference between the points A and D is

$$\phi_D - \phi_A = V = \varepsilon - I(r + R_A), \tag{4}$$

where V and I are the voltmeter and ammeter readings, correspondingly. Since there are two unknown quantities in Eq. 4, it is necessary to perform measurements twice (for two different resistors).

Write down the system of two equations for determination of ε and r. Derive formulae for calculating of ε and r. Prepare the Table for experimental data (as an example Table 2).

Task 3. Measurements and calculation of a nonuniform circuit

Draw a circuit diagram in your notebook (Figure 5).

Write down formulae for calculations: current and voltage between points 1 and 4 under a closed switch, voltage between points 1 and 7 under an opened switch.

Prepare the Table 3 for your experimental data.

Table 2:

N_{source}	N_{meas}	I (mA)	V (V)	ε (V)	r (Ohm)
1	1				
1	2				
2	1				
2	2				

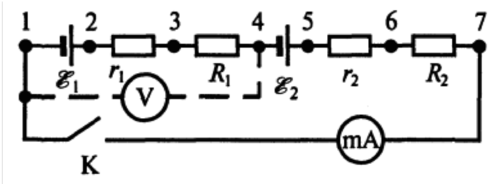

Figure 5:

Table 3:

Number	V_{closed} (V)	V_{opened} (V)	R_{sum} (Ohm)
1-2			0
1-7			

4 Measurements and data processing

4.1 Task 1. Determination of unknown resistance using ammeter-voltmeter based method

Measurement of resistance with the first circuit's configuration

a. Assemble the circuit with one of the unknown resistors (Figure 3(a)). You can use anyone of two proposed DC power supplies. Set a range of measurements close to 1 A for the ammeter and 12 V for the voltmeter. Set the wiper of the variable resistor at the middle position. Evaluate at which part of the scale the pointer of the measuring devices has deviated. To increase the accuracy of measurements, it is necessary that the pointer is on the right side of the scale.

b. Check the instrument readings. Write down the data in the Table 1.

c. Move the wiper 5 cm to the right. Write down the readings of the instruments.

d. Move the wiper 5 cm to the left regarding its original position. Write down the readings of the instruments.

e. Disable the right-hand of the voltmeter (in Figure 3(a)). Write down in the notebook the readings of the ammeter as I_0^I. Compare I_0^I with the result in the previous measurement (less, greater, equal). How does the connection of the voltmeter influence on the current in the circuit?

f. Having performed the measurements, turn off the power supply.

g. Determine of an internal resistance of the voltmeter R_V.

h. Calculate the resistance R_{red} for every measurement and determine its average value.

i. Perform the same measurement with R_{green} resistor.

Measurement of resistance with the second circuit's configuration

a. Assemble the circuit (Figure 3(b)). Perform similar measurements with two resistors.

b. Disable the left-hand of the voltmeter. Write down the readings of the ammeter as I_0^{II}. Compare I_0^{II} with the previous measurements and estimate the influence of the voltmeter on the current in that configuration of the circuit.

c. Turn off the power supply.

d. Determine of an internal resistance of the ammeter R_A.

e. Calculate the values of unknown resistors.

f. Compare the results obtained with the two different circuit configurations. Check the values of the resistors with the digital multimeter.

4.2 Task 2. Determination of emf and an internal resistance of a power supply

a. Use vitrified resistors for modeling an internal resistance of power supplies. Assemble the circuit (Figure 4).

b. Turn on the circuit and write down the readings of the measuring devices.

c. Change the resistor and write down the readings in that case.

d. Calculate the values of ε and r. Check the correctness of your measurement with the digital multimeter.

e. Make a similar measurement with another a power supply.

4.3 Task 3. Measurements and calculation of a nonuniform circuit

a. Assemble the circuit in Figure 5 without the voltmeter. Calculate an expected value of current I_{theor}. Switch on the keyswitch and measure the current I_{exp}. Compare I_{theor} and I_{exp} values.

b. Assemble the circuit in Figure 5 without the ammeter. Switch on the keyswitch and measure the voltage by connecting the voltmeter alternately to different points of the circuit . Write down the results into Table 3.

c. Then switch off the key switch and measure the voltage V_{1-4} and V_{1-7}. Write down the results into Table 3.

4.4 Task 4. Construction of potential diagrams

The potential diagram (in Figure 2) relates the values of the resistance at different points of the circuit (a horizontal axis) and the values of a potential at corresponding points (a vertical axis).

a. Calculate and write in the right column of Table 3 the value of the sum of the resistances between the corresponding points of the circuit.

b. Use graph paper for your plot. Choose the appropriate scale range for each axis. Put the relevant experimental points on the resistance axis (with their corresponding numbers from Figure 5).

c. Add the voltage data to the plot with taking into account a voltage sign. Connect the points with straight lines.

d. Analyze your diagram. The potential diagram at points 1,2 and 4,5 should be a vertical line with the length corresponding to the emf value. Line segments between points 2, 4 and 5, 7 must be parallel to each other, and the tangent of their slope equals to the current in the circuit.

e. Plot at the same graph data for open-ended circuit. Make sure that at the ends of the open circuit the potential difference is equal to the algebraic sum of all the emfs in the circuit.

5 Questions

1) What is constant in a battery?
2) The Ohms law for DC circuits. What are the conditions for the validity of Ohm's law.
3) The Kirchhoffs rules. Application of the Kirchhoff's rules for derivation of the used expression for ε and r.
4) What determines the appropriateness of the choice of the ammeter-voltmeter method for measurement of resistance? What are the advantageous of each circuit configuration of the ammeter-voltmeter method?
5) Potential diagram. What is the physical meaning of the tangent of the slope of the lines on the potential diagram to the horizontal axis?