Practical 2.2
EXTENSION OF THE RANGES OF ELECTRICAL MEASURING DEVICES

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1 Introduction

An important characteristic of the electrical instrument is its internal resistance R_{instr}. During the measurements the instrument becomes an additional element of the circuit under test and may cause the measured characteristics to change because of the instrument own parameters. When the instrument is connected in series to the circuit (as an ammeter), its internal resistance should be small in order to minimize the voltage drop across the instrument. However, when an instrument is connected in parallel (as a voltmeter), the instrument resistance should be greater in order to reduce the current flow through it. The internal resistance of the instrument is indicated in a technical passport or on its front panel or can be measured.

When R_{instr} is measured directly with a usual ohmmeter (or multimeter), however, a special care should be taken to not disable the instrumentation by the over range current provided by the ohmmeter. In this method, the resistance of the ohmmeter and the leads remain unknown. One of the methods invented for precise measurement of the resistance is the **Wheatstone bridge** method, in which a variable resistance is used in order to obtain a balance between the bridged branches of the circuit.

1.1 Measurement of resistance with Wheatstone bridge

To analyze its operation, consider the simplified electric circuit (Fig. 1) The circuit consists of two resistors connected in series. Since there is the same current through these resistors, its value in accordance with the Ohm law is $I = V_1/R_1 = V_2/R_2$. Hence $V_1/V_2 = R_1/R_2$. Such circuits are called potential dividers (or voltage dividers). The Wheatstone bridge represents two potential dividers connected in parallel (Fig. 1). Points, at which the resistors are connected in series, are bound by a bridge with a galvanometer (G). The bridge is said to be balanced when the potential difference between the points A and C equals to zero, and there is no current flow through the galvanometer. Obviously at the point of balance, the ratio is

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

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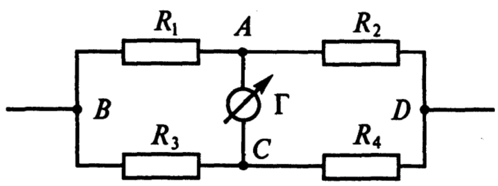

Figure 1: A simplified circuit of a Wheatstone bridge.

If the value of any resistor is unknown (e.g. R_1), it is possible to balance the bridge by adjusting the resistors and fixing zero current with a galvanometer. Then, the uknown resistance can be determined as

$$R_1 = \frac{R_2 \times R_3}{R_4}$$

.

An important advantage of this circuit is that the measured resistance R_1 does not depend on the values of resistors R_3 and R_4 but only on their ratio. These resistors can be selected in such a way as to ensure a minimum current flow through the unknown resistor which would be quite useful if the instrument resistance should be measured.

1.2 Extending the range of ammeters and voltmeters

The ranges of electrical measuring instruments (whether ammeter, voltmeter, or any other type of meters) are limited by currents, which may be carried by the coils of the instruments safely. For example, the moving coils of the instruments can carry maximum current of about 50 mA safely and the potential drop across the moving coil is about 50 mV. Hence, it becomes necessary that the current and voltage being measured be reduced and brought within the range of instrument.

Common devices used for extending the range of the instruments are

a. Shunts

b. Multipliers

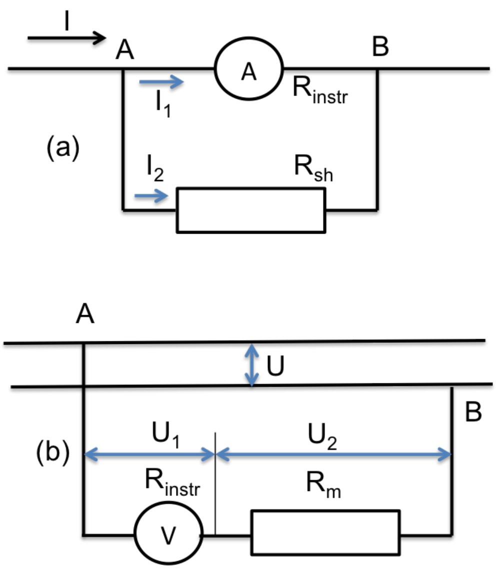

Figure 2:

Shunts: The range of an ammeter can be extended by connecting a low resistance, called shunt, connected in parallel with ammeter. So, the current will be distributed between the two branches in such a way that an appropriate (i.e., safe) amount would go through the ammeter, and the over range (i.e., extra) current would be bypassed through the shunt resistance. (Figure 2(a)).

The shunt resistance can be determined as $R_{sh} = R_{instr}/(n-1)$, where $n = I_{new}/I_{max}$, I_{new} is the total current and I_{max} is the maximum current passing through the instrument. A measuring instrument together with a shunt resistor becomes a "new" device with an extended measurement range. The resistance of a "new" ammeter is always less than the resistance of an initial device by a factor of n.

Multipliers: The range of voltmeter can be extended by connecting a high resistance, called multiplier in series with the voltmeter (Figure 2(b)). The multiplier limits the voltage drop so that it does not exceed the value of full scale and thus prevents from being damaged.

The multiplier resistance can be determined as $R_m = R_{instr} \times (n-1)$, where $n = V_{new}/V_{max}$, V_{new} corresponds to the new voltage range, V_{max} is the maximum allowed voltage at the voltmeter.

The voltmeter together with the multiplier transforms to a "new" instrument with an extended measuring range and an increased internal resistance by a factor of n.

Multifunctional devices that combine an ammeter and a voltmeter contain both a set of multipliers and a set of shunts.

2 Experimental tasks

1. Measure an internal resistance of an ammeter using the Wheatstone bridge.
2. Determine a value of the shunt resistor and test a new ammeter with an extended measuring range.
3. Determine a value of multiplier and test a new voltmeter with an extended measuring range.

Equipment: digital multimeter, analogue measuring instrument, DC power supply, variable resistor, connecting wires.

3 Experimental setup

The diagram of the experimental setup based on the Wheatstone bridge is shown in Figure 3.

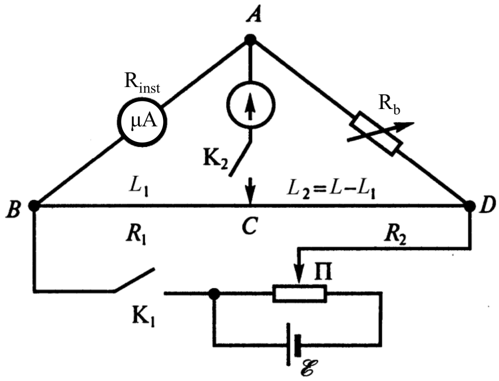

Figure 3:

The upper part of the bridge consists of an ammeter (μ A) and a resistor box R_b. You should measure the internal resistance of the ammeter R_{instr}. You need to use switches at the resistor box R_b to achieve the balance of the bridge.

In the lower part of the bridge (points B and D), a variable resistor is used. The wiper of the resistor divides the lower part of the bridge in two arms. The balance equation for a given construction can be determined as

$$\frac{R_{instr}}{R_b} = \frac{R_1}{R_2},$$

where R_1 and R_2 are resistances of the left and right parts of the variable resistor.

The resistance of a wire is known to be proportional to its length. So, one can write

$$R_{instr} = R_b \times \frac{L_1}{L_2}$$

, where L_1 and L_2 are length of the two parts of the variable resistor.

The length of the left part L_1 and the total length L can be determined by means of a ruler along the variable resistor. Then, the length of the right side is $L_2 = L - L_1$.

The balance of the bridge is monitored by a galvanometer, i.e. a sensitive microammeter with a "zero" in the middle of the scale. The galvanometer is placed between the wiper of the variable resistor (point C) and the point A through the switch K_2.

To limit the electric current through the device under investigation, the circuit is biased by DC power supply through a potentiometer P, which is an adjustable voltage divider.

The diagram of the second setup to test the accuracy of selection of the shunt resistor is presented in Fig. 4. The test device (μA) is connected to the resistance box that is used as a shunt resistor R_{shunt}. In this circuit, a multimeter is implemented to measure the total current. The magnitude of the current is adjusted by the variable resistor R.

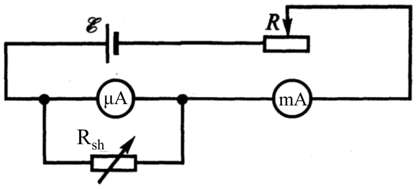

Figure 4:

The diagram of the third setup to test the accuracy of the multiplier is presented on Fig. 5. The magnitude of the voltage at the test device (μ A) is set by a potentiometer.

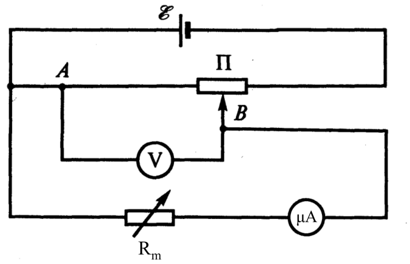

Figure 5:

4 Preparation of protocols

Task 1. Measurement of resistance of the ammeter

Draw a circuit diagram in your notebook (Figure 3). Write down and derive the formulae for calculating of R_{instr}. Prepare the Table 1 for your records of experimental data.

Table 1:

N	L_1 (cm)	R_b (Ohm)	$L_2 = L - L_1$ (cm)	L_1/L_2	R_{instr} (Ohm)	ΔR (Ohm)
1						
2						
3						

Calculate and write down the average values of R_{instr} and ΔR.

Task 2. Determination and selection of a shunt resistor

Draw a circuit diagram (Fig. 4). Write down and derive the formula for calculating R_{sh}, $n_{calc} = I_{given}/I_{max}^{instr}$, $n_{exp} = I_{meas}^{new}/I_{meas}^{instr}$, deviation of the experimental value of n from the calculated value $\delta n = n_{exp} - n_{calc}$ and $\varepsilon_n = \delta n/n_{calc}$ (in %) with the description of all symbols. Prepare the Table 2 for your measurement results.

Table 2:

N	I_{meas}^{instr} (μA)	I_{meas}^{new} (mA)	n_{exp}	δn	ε_n
1					
2					
3					
4					
5					

Calculate and write down the average values of n_{exp}, δn and ε_n . Leave some space in the notebook for calculations.

Task 3. Calculation and selection of a multiplier resistor

Table 3:

N	V_{meas}^{instr} (V)	V_{meas}^{new} (V)	n_{exp}	δn	ε_n
1					
2					
3					
4					
5					

Draw a circuit diagram (Fig. 5). Write down and derive formula for calculating R_m, n_{calc}, n_{exp}, δn and ε_n, describing all the symbols in these formulae. Prepare the Table 3 for recording measurement results.

Calculate and write down the average values of n_{exp}, δn and ε_n . Leave some space in the notebook for calculations.

5 Measurements and data processing

5.1 Task 1. Measurement of the internal resistance of an ammeter

a. Assemble the experimental circuit (see Fig 3). The variable resistor is indicated by "B" and "D" points in Figure. Connect the lower part of the Wheatstone's bridge to the power supply through the double-key switch K_1. Connect one of the terminals of K_1 to the "+" of the source, the second one of K_1 to the point B and the point D to the wiper of the variable resistor. Connect the upper part of the bridge to the "+" terminal of the test device. The second terminal of the test device should be connected to "point A". Connect the terminal "∗" of the resistance box to "point A" and the terminal "9999.9" of the resistance box to "point D".

b. Connect the middle clamp of "point A" to the wiper of tha variable resistor through the Galvanometer and the switching key K_2.

c. Set the wiper of the variable resistor at the middle posittion, the wiper of the potentiometer on the left position (as in Figure). Switch the resistance box to the 200-ohm mode.

d. Fill in the Table 1 with values of L_1 and L_2, taking into account the total length of the variable resistors $L = 1$ m.

e. Turn on the power supply. Switch on K_1 only. Set the current through the ammeter at a level of $0.5 - 0.8 I_{max}$.

f. Switch on both keys for a short time and observe the deflection of the pointer of the galvanometer. Turn off the keys and set 300-ohm mode on the resistance box.

g. Turn on both keys again. When the pointer deviates in the same direction and the deviation is weaker, you are approaching the balance of the bridge. In this case, you should turn off the keys and again increase the resistance of the resistance box. Keep on until the bridge will be balanced. Write down in the Tab. 1 the value of R_B corresponding to the balance of the bridge.

h. On the resistance box, set the resistance $\sim 30\%$ lower than the found R_B. Slowly moving the wiper, find the point which corresponds to the "zero" current through the galvanometer and write down the corresponding lengths of the wire resistor. Set the resistance $\sim 30\%$ higher than the former R_B. Slowly moving the wiper, again find its appropriate position and write down the corresponding lengths of the wire resistor.

i. Calculate R_{instr} for each measurement. Using the data obtained in three measurements, determine the average value of the device resistance, calculate the absolute uncertainty for each measurement $\Delta R = R_i - R_{avg}$ and the average error ΔR_{instr}. Fill in Table 1 with the results.

5.2 Task 2. Selection of a shunt resistor

a. Write down the necessary data of the device from its specifications. In our case the measurement range of the test device I_{max} corresponds to μA. Ask an engineer for a new value of the measurement range of the device I_{given}. Determine the value R_{shunt}. Prepare a multimeter to measure the current I^{new}_{meas}.

b. Assemble the experimental circuit (in Fig. 4). Connect the power supply, the variable resistor, the tested microammeter and multimeter in series. Connect the multimeter in parallel to the resistance box acting as a shunt. Set switches of the resistance box at position of R_{shunt}. Move the wiper of the variable resistance to the position of its maximum resistance.

c. Set the pointer of the microammeter at the maximum of its scale. Fill in the Table 2 with multimeter readings as I^{new}_{meas} and micrometer readings in scale units. Repeat this procedure, setting the pointer of the microammeter to 3/4 and at the middle of its scale.

d. Calculate n_{exp}, δn, their average values and ε_n.

5.3 Task 3. Selection of a multiplier

a. Determine the measurement range of V_{max} and the scale division value (in volts) of the test microammeter when it is used as a voltmeter. Ask an engineer for a new value of the measurement range V_{given}. Calculate R_m using the value of R_{instr}, V_{max}^{instr} and V_{given}.

b. Assemble the experimental circuit (in Figure 5). Connect the test microammeter in series to the resistance box which plays a role of multiplier. Connect this circuit to one of the terminals of the variable resistor and its wiper. Connect the multimeter in parallel with these elements.

c. Prepare the multimeter for measurements. Set R_m on the resistance box.

d. Using the variable resistor, set the pointer of the microammeter to its maximum. Record readings of the microammeter I_{instr} (in scale units) and the multimeter U_{meas}^{new}. Repeat measurements by moving the pointer of the microammeter at 3/4 and at the middle of its scale.

e. Calculate n_{exp}, δn, their average values and ε_n. Fill in the Table 3 with these quantities.

6 Questions

1) How does an ammeter change the current in the circuit?

2) Why should the ammeter resistance be as low as possible?

3) How does a voltmeter change the current in the circuit?

4) Why should the resistance of the voltmeter be as large as possible?

5) How to determine the internal resistance of a measuring device?

6) Shunt. What is it? What is used for? Derive the formula for calculating R_{sh}. How does the shunt connect to the ammeter? Compare the resistance of the ammeter with a shunt and without.

7) Multiplier. What is it? What is used for? Derive the formula for calculating R_m. How does the multiplier connect to the voltmeter? Compare the resistance of the voltmeter with the multiplier and without.

8) Explain the operation of the potentiometer as a voltage divider.