



Crystal Clear Electronics

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05 - Multimeter, Ohm's Law in Practice

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MULTIMETER

In this section, we deal with the multimeter and its simple measurements. We learn to measure voltage, current, and resistance, and we get to know the parallel and serial connection modes of resistors and their load capability.

Let's start with what exactly is the multimeter. The word itself comes from two Latin words, „multi” and „meter”. The word „multi” means a lot, more, diverse – think about the multivitamin. The word „meter” comes from the Latin word „metrum”, whose original meaning is measure. This word refers to the measuring instrument, similar to the words of the voltmeter (voltage gauge), manometer (pressure gauge), anemometer (air speedometer). The name of the device therefore suggests that we are talking about a measuring device suitable for measuring a wide range of quantities. Actually, we are close to the truth with the limitation that we are limited to measuring electrical quantities.

What can be these quantities? In the simplest case they can be voltage, resistance, and current. The names of the built-in instruments measuring them are: Volt-meter, Ohm-meter, Ampere-meter. Older analog multimeters were capable to measure roughly these quantities. These features have been added to modern digital measuring devices with additional capabilities: capacitor capacitance measurement, signal frequency measurement, coil inductance measurement, open-circuit, diode, or transistor tester, or possibly thermometer. These functions are not necessarily found in every multimeter, the number of measurable quantities depends on the type of product.

First, let's familiarize with the general design of the device, and its proper connection. The multimeter consists of three well-distinguishable parts: a wide digital display, usually located at the top section, a rotary switch in order to select the quantity to be measured and the input connectors to which the measuring cables can be connected. In some simple multimeters, the measuring cables are fixed to the case, and there are no connectors, the wires come directly from the multimeter. This makes difficult to replace a potentially defective measuring cable, and also contains other hazards that will be discussed later at the current measurement.

In addition to the above, there are additional buttons below the display. For example, on mine, there is a yellow HOLD label on the left, and a light blue on the right, showing a pictogram symbolizing the sun. The first one can store the currently displayed value. When pressed, the display shows the value that was measured at the moment of pressing. The measurement can be continued by pressing the button again. The latter blue button is used to turn the display backlight on and off.



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ROTARY SWITCH POSITION

Let's take a look at what options you can choose on the rotary dial! If you move clockwise, in the first large group, you will see a letter V with a continuous and dashed line. With this setting, voltage can be measured in DC circuits. The different numbers refer to the measurement limit, which on this multimeter is as follows: 200 mV, 2000 mV, 20 V, 200 V, 250 V. We will get to know with the measurement and the significance of the measurement limits later, however, we note in advance that the instrument always shows the measured quantity in a unit of measurement corresponding to the given measurement limit: if the measurement limit is 2000 mV, then in mV, if 2V, then in V.

On the rotary dial, the next group is the alternating voltage measurement options. The alternating voltage is mainly for high-power systems, such as at home the 230V power outlets. (Alternating voltages over 50 V can be dangerous to our lives, we should not do such measurements alone, without the supervision of an expert!) This topic will not be discussed here, because the curriculum is mainly about DC circuits.

In the next position, we see a sign of a diode and a signal indicating an acoustic signal. In this position, **open-circuits** can be determined, and the forward voltage of semiconductor components (diode, transistor) can be measured. You can read more about these in the following sections.

At the next position, we see a so-called **square wave**, and an OUT label. In this case, the multimeter operates as a nearly 50 Hz square wave generator, for example, when testing and repairing audio devices.

Next to the next large group we see a letter A, and the same continuous and dashed line as before for DC measurement. From this, you could already guess that using these settings, **we can measure DC current** in different circuits (2000 μ A – 10 A). We will learn more about this soon. **It is important** that we do not use these positions on the rotary dial until we have read the current measurement section, because we can damage our measuring instrument.

Finally, the last big group we get to know is **the resistance measurement** options that the big Ω stands for. Here the measurement limits range from 200 Ω (Ohm) to 200 M Ω .

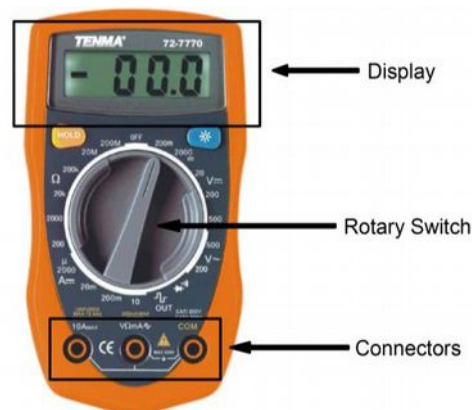


Figure 1 - The main parts of the multimeter

CONNECTING THE MULTIMETER

Before we can use the multimeter, we need to connect measuring cables to the appropriate input connectors. Black to the right COM subtitle! The term COM here refers to the word „common”, which means common point, in this case the ground, zero point. This will be the reference point for our



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measurements. And if we don't get another instruction, the red cable should always be connected to the middle where we see $V\Omega mA$. It is important to note that for certain multimeters there is a separate connector for $V\Omega$ (voltage and resistance measurement), and mA (current measurement in mA range) measurements. For these devices, the red wire should generally be connected to the $V\Omega$, except for the current measurement, where it should be connected to mA or A, depending on the current. This method protects the device, so it becomes more difficult to accidentally damage the multimeter. This will be described in more detail in the current measurement section.

It should be noted that the choice of the colour of the cables comes only from customary practice. If we deviate from these, we will change the red and black cables, or we might use other colour wires, that will not affect the measurement, but it would be difficult for us and our companion to help us.

VOLTAGE MEASUREMENT

Let's start with the simplest case, which is DC voltage measurement. We can measure the voltage between two points. In this case, the multimeter is always connected in parallel to the components or equipment to be measured. The voltage meter is considered to be ideal, so it works as an open circuit, no current flows through it.

When the voltage meter is connected to the circuit in series, it interrupts the circuit, and the circuit won't operate normally. (This can be our goal when we try to find an error, but then the circuit is not in its original state.)

In reality, of course, the measuring instrument does not behave as an ideal open-circuit, but as a high-value resistor, which is usually noted on the instrument by the manufacturer. That's 10 M Ω in case of my multimeter. While the resulting resistance of the measured circuit network is below 10 k Ω , the input resistance of the multimeter is infinite, and the multimeter is considered to be as an open-circuit. However, this value depends on the input resistance mentioned above, i.e. the type of the multimeter. Of course, if the network to be measured has a higher resistance, then we can measure it, but the measurement will be more inaccurate, and the operation of the circuit will be more and more different from the original. We will discuss the reason and theoretical background later, when we will discuss the parallel connection of resistors.

Turn the rotary dial from the "off" position to the right (clockwise) where DC voltage can be measured with a 20 V measurement limit. The measurement limit should be chosen so that it is set to the lowest possible value, which is definitely greater than the value to be measured. In this way we can measure the most accurately. Modern digital multimeter protection against overvoltage is generally good. If we accidentally choose too small measurement limit, then no serious trouble can happen. In this case, the multimeter with 1 on the left side of the display indicates that the signal to be measured is greater than the selected measurement limit.

Start by measuring the voltage between the terminals of our 12V AC/DC power supply. Connect the power supply to the breadboard and measure the voltage between the two pins.

It is important to pay close attention **not to short-circuit the power supply with the metal tips at the end of the measuring cables**, when measuring between points near each other. Always take care that the probe only touches the selected point in the circuit! If one of the tips reaches the circuit inadvertently



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between more points at the same time, then these points will be short-circuited, which usually does not mean danger to the measuring instrument but can damage the circuit or the power supply. It depends on what you “managed” to short-circuit. If we are not sure, let’s put two wires to the breadboard. Connect one to the negative line (rail) and the other to the positive line. Then touch the black measuring cable to the negative terminal and the red to the positive terminal (or to the end of the corresponding newly connected wires). Make sure that the contact between the measuring cable and the point being measured is correct during the measurement. If the value on the display fluctuates significantly, the contacts may not be correct. If we did everything well, our instrument would show about 12V. In my case, it was 12.15V.



Figure 2 - Measuring the supply voltage

Comment

If our instrument shows a value of around -12 V, then something is either connected reversely to the breadboard or to the other side of the instrument. The black measuring cable indicates always the ground point, and the device shows the potential point of the red measuring cable. A negative value means that the wire has a lower potential point. If the multimeter is well connected, then it is likely that the power cable terminals have been replaced.

If we got this, then measure the voltage at two resistors connected in series. Take two 1k Ω resistors and connect them in series and to the power. Then measure the voltage at the two resistors. We need to get the same value, as in the previous measurement: the power supply.



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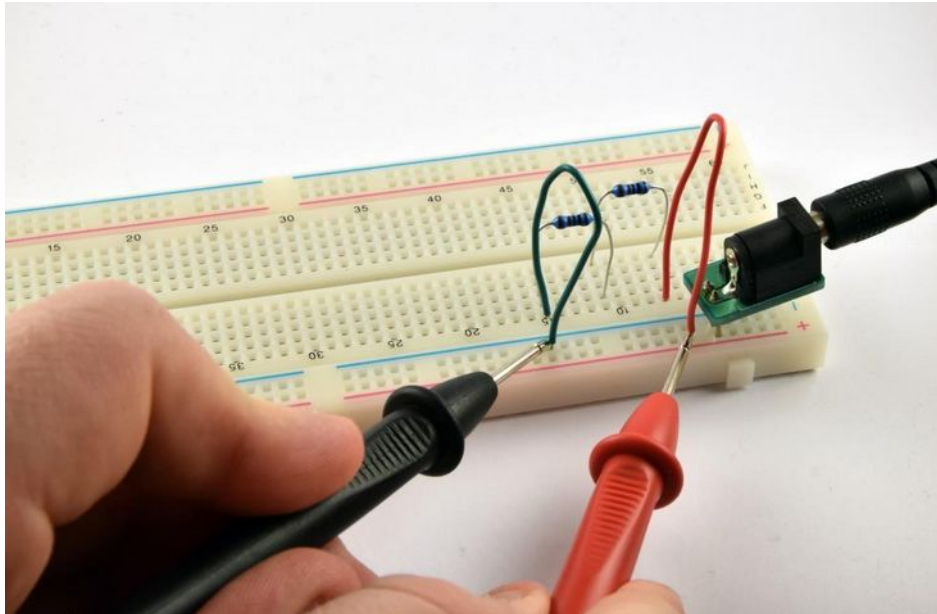


Figure 3 - Measuring the voltage at the resistors

Then measure the voltage at one of the resistors. Because they are connected in series, and have the same resistances, we know from our previous knowledge that half of the supply voltage drops across the resistor, which in my case is 6.08 V. If you don't remember the theory anymore, there's no problem. After getting to know the other measurement methods, we will return to connect resistors in series and in parallel.

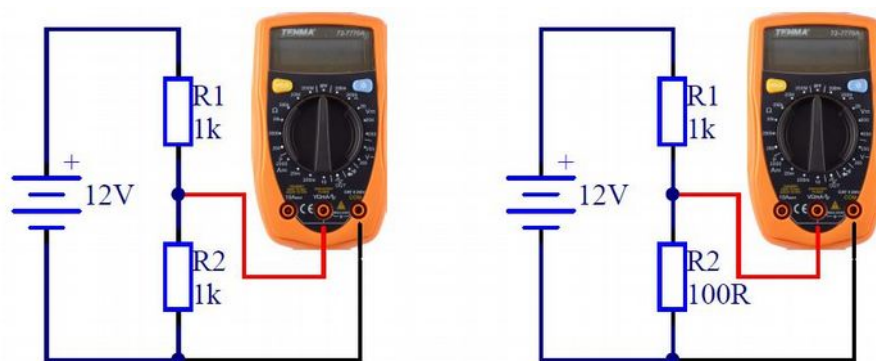


Figure 4 - Measuring voltage drop across resistors of different sizes (left: 1kΩ, right: 100Ω)

Now replace one of the 1 kΩ resistors to 100 Ω. Then the voltage at 100 Ω is:

$$U_2 = \frac{100 [\Omega]}{100 [\Omega] + 1000 [\Omega]} \cdot 12.15 [\text{V}] = 1.105 [\text{V}]$$

Let's measure it as well! The multimeter display shows 1.10 V. Note that this is less than the next measurement limit, which is 2000 mV = 2 V so it can also be used. Adjust the rotary dial accordingly, then re-measure the voltage-drop on the smaller resistor. The instrument indicates 1102 mV at me. By adjusting the measurement limit, we were able to get one more valuable digit and so to get a more accurate result.



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The calculated and measured results are slightly different. The reason for this is that the true value of the resistors differs from the nominal value due to manufacturing inaccuracy, that is, what is written on it, and that our instrument also has measurement inaccuracy.

Comment

The manufacturer guarantees the maximum percentage of this deviation. This is indicated by the last strip of the resistor colour code (Silver: $\pm 10\%$, Gold: $\pm 5\%$, Red: $\pm 2\%$, Brown: $\pm 1\%$, Green: $\pm 0.5\%$).

At resistance measurement, I promise that we will refine our previous calculation. If you like, find out more examples of serial-parallel connections, calculate them and control them by measurement. After getting to know the resistance measurement, we will look at several examples.

In summary: It is easy to measure voltage, but attention should be paid not to short-circuit with the metal tip of the measuring cable nearby metal surfaces, otherwise the measured equipment can be destroyed. During the measurement, we can measure using the red cable relatively to the point we touched with the end of the black measuring cable.

CURRENT MEASURING

Let's learn the following function of the multimeter: how to measure current. This measurement is more complicated than the voltage measurement, and if it is used incorrectly, we can destroy our instrument. In contrast to voltage measurement, here the multimeter is always connected in series to the circuit, because we can, and we want to measure the current flowing through the device. Wiring in this way makes the measurement difficult, since the circuit must be opened at the point to be measured.

There is also a serious threat in case of this measurement. In order that the connected instrument does not affect the measurement, it was designed so that its resistance is very small, which means the risk that if we set up our measuring instrument for the current measurement and accidentally connect it between points, where high current (for example the output of our power supply unit) can be flowing, that can also **damage both the circuit and the measuring instrument**. Pay attention to this during the measurement!

When measuring current, the current direction is positive if it flows into the red wire and the black out, then you see a positive number on the display. The negative is if it flows in the other direction.

Choosing the right measurement range for this measurement is not a task without danger. In this case, the measuring instrument has a small resistor value, which is different in case of different measuring ranges, and insignificant from the point of view of the circuit. The value of the resistor used to measure smaller currents is higher, which results, that the higher current flows the heater the resistor gets, or even burns. (With this phenomenon we will learn more about load capacity of resistors at the end of the curriculum.) Therefore, the correct selection of measuring limit has a great importance. If we are uncertain about the amount of electrical current to be measured, it is worthwhile to try a larger measurement first.

In order not to break the measuring instrument so easily, a fuse is built into it. If you look more closely at the device, there is a "FUSED" title above the centre connector, which means that it is equipped with a fuse. Its task is to interrupt the circuit in case of excessive current, thus protecting the measuring device against serious damage. The fuse insert has a nominal value, which is the current where it unlocks. This



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value is usually written on the instrument (above the “FUSED” inscription), which is 200mA in case of my multimeter. If I would measure a current higher than this value, my fuse insert would unlock, which would protect the rest of the instrument, but unfortunately, I would have to replace the fuse insert.

There is a limit of 10 A on the rotary switch, above which we can read “UNFUSED”, i.e. without a fuse. It is also described here that at such a high current value we can measure for a maximum of 10 seconds with a break of at least 15 minutes. If large currents are measured further or more frequently, the multimeter may overheat and destroy. In conclusion, if we connect the red wire to this “UNFUSED” connection point, we can extend the measurement limit, but we lose the protection functions provided by the fuse.

I have already mentioned that there are also multimeters, where the measuring cables are fixed to the case, which means that unfortunately we cannot choose how to connect the measuring cables to our multimeter. For such devices, be sure to read the instructions before use, and what nominal current is allowed!

Here is a summary of what is happening in the measurement of the different currents for the two different wiring modes (“FUSED”, “UNFUSED”).

Current	“FUSED” wiring with fuse	“UNFUSED” wiring without fuse
0-200 mA	Recommended! The instrument measures correctly, if the measuring limit is correctly set with the rotary dial.	Inaccurate and therefore not recommended. The instrument measures correctly, if the measuring limit is correctly set with the rotary dial.
200 mA-10 A	Avoid! The instrument has a fuse to protect it from further damage. The fuse insert must be replaced.	Recommended! The instrument measures correctly, if the measuring limit is correctly set with the rotary dial. Attention should be paid to the measurement time; the instrument may overheat.
Greater than 10 A	Avoid! The instrument has a fuse to protect it from further damage. The fuse insert must be replaced.	DANGER!!! The instrument is overloaded and can be destroyed at any moment.

Before starting the measurement, we must definitely estimate the current to be measured. Often, there is a resistor connected in series in the branch to be measured. If we know the value of the resistance, we can deduce the current from the relatively easily measurable voltage on it. If there is no possibility for such a measurement or estimation, please refer to the datasheet of the given device. If we cannot finally estimate the current, then choose the 10 A measurement limit (with the corresponding wiring!) and then reduce it if possible, as we previously learned from the voltage measurement.



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Prepare our previous connection used at voltage measurement, which consisted of two resistors (100 Ω and 1 k Ω). First, estimate the current based on the previous measurement! On the smaller resistor, the following estimate can be given for the current from the already measured voltage:

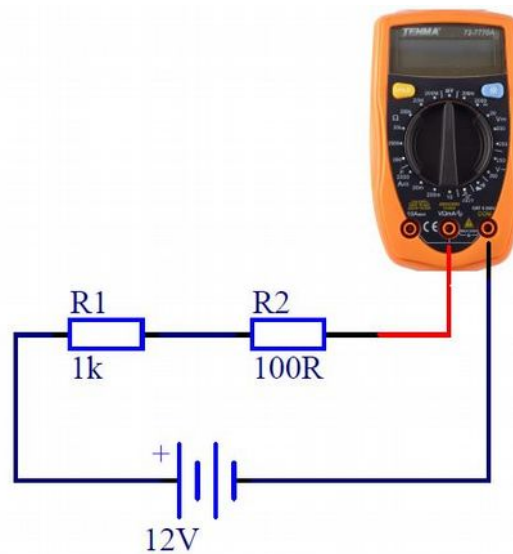


Figure 5 - Flowing current measurement

$$I = \frac{U_2}{R_2} = \frac{1.102 \text{ [V]}}{100 \text{ [\Omega]}} = 0.011 \text{ [A]} = 11 \text{ [mA]}$$

So, we can safely measure with the 20 mA measurement limit. For current measurement, turn off the circuit to be measured, in this case disconnect the power supply. If you are ready to do this, then disconnect the circuit at the point where you want to measure. Because the current is the same everywhere in serial connection (within one branch), we can do it anywhere. Connect one of the wires of the assembled circuit from the resistor to another blank row on the breadboard. After turning the circuit back on, touch one of the measuring tips to the end of the empty row, and the other to the end of the resistor. Then, by touching, the circuit is closed, if any of the ends is released, there will be no flow, the “equipment” switches off. If we did everything well, the measured current is displayed on the instrument, which in my case was 10.97 mA. If you like, you can make sure that you measure the same current in the branch everywhere.

In summary, current measurement should only be performed with due care, because both the circuit and the multimeter can be destroyed. If there is a known valued resistor in the branch to be measured, it may be appropriate to trace back the measurement to voltage measurement, as we have done in case of the estimation. If the value of a resistor or the voltage on it is known, then the current flowing through it can be calculated.

If the previous one is not possible, follow these steps:

1. Estimate the quantity to be measured, select the measurement limit, connect the measuring cables to the multimeter accordingly.
2. Turn off the circuit!
3. Disconnect the circuit at the measured point and connect the multimeter in series.



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4. Perform the measurement, if we measure a current greater than 200 mA, be careful not to overheat the instrument. (For example, for large currents, we take a minimum break of 15 minutes for a maximum measurement of 10 seconds.)
5. When the measurement is complete, turn off the circuit, and restore its original state.

RESISTANCE MEASUREMENT

Resistance measurement is also one of the simplest measurements. In this case, the measuring cables are touched to the two ends of the component to be measured. Here, the wiring method is arbitrary, as the resistance can only be positive. The wrong choice of measurement range is not a problem either. If we select too low, this will be indicated by 1 on the left side of the display, just like in case of the voltage measurement.

The only difficulty with this operation is to measure resistance, when the resistor is already built into a circuit. In general, other components are connected in parallel with the resistor to be measured. And then we would not measure the resistance of the selected part, but the resulting resistance of the components that were connected to it. The only solution for this is to remove the component, solder it out from the circuit, and measure it. (Before we disassemble any electronic circuit, make sure that it is switched off!) If possible, it is advisable to perform the measurement before installation.

For the sake of accuracy, care should be taken to ensure correct measurement. In order to make the contact between the leg of the resistor and measuring tips adequate, it may be expedient to clamp them together with our thumb. Note however, that in this case, the component is connected in parallel with our own body. The resistance of our body falls into the order of magnitude of the few M Ω , so it mainly cause inaccuracy such a solution in case of a measurement above 10 k Ω resistors. We prefer to measure resistance on our table (made of non-conductive material). Use the tip of the measuring cables to push the terminals and ends of the component onto the table. In this case, if it is difficult to hold the component firmly, you can use your thumb at the tip of one of the measuring cables, but not both. If possible, the resistor can also be plugged into an empty portion of the breadboard, which makes it easy to ensure proper contact between the resistor and measuring cables.

For through-hole resistors, we can use a tricky solution. Pull the measuring cables out of the multimeter and plug one of the legs of the resistor into one, and the other one into the other measuring line.

Remove the 100 Ω resistor from our previously assembled circuit and measure it separately from the rest of the circuit. Choosing the measurement limit of 200 Ω , the instrument shows me 99.3 Ω . (If the value fluctuates very much, then it means that the contact is not correct. Try to fix it anyway!) We can see that the resistance is slightly different from the nominal value. Since we have already measured voltage and current on this resistor, we can calculate the value of the resistance:

$$R = \frac{U}{I} = \frac{1.102 \text{ [V]}}{0.01097 \text{ [A]}} = 100.1 \text{ [\Omega]}$$

The measured and calculated resistance value does not match perfectly. The reason for this is that the multimeter also has inaccuracy, it does not measure any value perfectly, but in most cases, it is enough for us.



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In summary: Resistance is easy to measure. Incorrect selection of the measurement limit is not dangerous. The component is always measured with the removal of the coupling / soldering, and nothing (for example, our own body) should be connected in parallel with the resistor during the measurement.

CONTINUITY TEST

The last function of the multimeter we will get to know is the measure of continuity. This provides a very useful debugging method. Often, when we build a circuit, we cannot be sure that all our soldering is adequate, or it may even happen that a broken wire prevents proper operation.

In other cases, our goal is to test to make sure there is no connection between two points. For example, when two component legs should be soldered close to each other, but at different points, we need to make sure that the two components are not in contact. These problems are easiest to detect using the continuity test function and then remedied.

Switch off the circuit before starting the measurement! The components under voltage in this measurement can damage the multimeter. Set the device's rotary switch to the position indicated by the diode and an acoustic signal. Then touch the tips of the measuring cables to the two points that you want to test for continuity. When you hear a beep, the resistance between the two points is less than 70 Ω (depending on the multimeter type).

(It is also possible to quickly verify the correct operation of the multimeter by touching the ends of the measuring cables in this position.)

OHM'S LAW IN PRACTICE

You got to know the Ohm's Law a bit before, but now we are going to explore its application possibilities a little more thoroughly. This law expresses that current (I) flowing through a resistor is always proportional to the voltage on it (U). The ratio of the two is called resistance, usually denoted by R and its unit of measurement is Ohm [Ω].

$$R [\Omega] = \frac{U [V]}{I [A]}$$

SERIAL CONNECTION

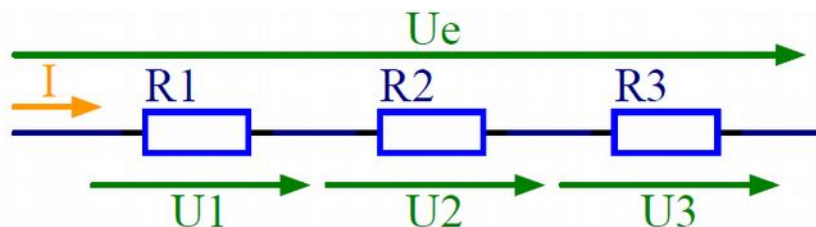


Figure 6 - Serial connection

It is given multiple resistors in series ($R_1, R_2, R_3, R_4 \dots$). Could we replace them with a piece of resistor so that nothing else in the circuit changes?



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The answer to the previous question is yes. The value of the replacement resistor should be as high as the total resistance of the original resistor network, i.e. **the resulting resistance**.

When we talk about the concept of the resulting resistance, we must always say which of the resulting resistance of resistors we are talking about. And to be able to calculate this, starting from Ohm's Law, a few simple mathematical transformations will make a relatively simple relationship.

In order that the circuit properties remain unchanged, the same current must flow through and the same voltage must be dropped on this replacement resistor as the original resistors. The current flowing through the serial circuit is the same everywhere, denoted by I . The voltage between the endpoints of a selected component will be equal to the sum of the voltages on each resistor (see Kirchhoff's voltage law). Let us denote this voltage with U_T as total voltage!

$$U_T = U_1 + U_2 + U_3 + \dots$$

Expressing the voltage on the single components using the Ohm's Law, we get the followings:

$$U_1 = I \cdot R_1$$

$$U_2 = I \cdot R_2$$

$$U_3 = I \cdot R_3$$

...

Replace U_1, U_2, U_3, \dots with these terms:

$$U_T = I \cdot R_1 + I \cdot R_2 + I \cdot R_3 + \dots$$

Score up the Ohm's Law for this imaginary replacement component, i.e. the equivalent resistance:

$$R_{EQ} [\Omega] = \frac{U_T [V]}{I [A]}$$

By replacing our previous equations and simplifying with the current, we get the following relationship:

$$R_{EQ} = \frac{(I \cdot R_1 + I \cdot R_2 + I \cdot R_3 + \dots)}{I} = R_1 + R_2 + R_3 + \dots$$

So, in case of serial connection, the resulting resistance is simply the sum of the resistances. This has two important applications.

One is that we can easily set any size of resistance. For example, if we need a 22 Ω resistor, but we only have 1 and 10 Ω resistors, we simply have to connect two 1 Ω and two 10 Ω resistors in series.

What is another important application? Suppose we have a 12 V power supply, and somehow, we want to produce 5 V. How can we do this with two serially connected resistors? Express the current in the main branch using the resulting resistance or one of the resistances:



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$$I = \frac{U_T}{R_{EQ}} = \frac{U_1}{R_1} = \frac{U_2}{R_2}$$

By converting the two right-hand connections we get:

$$\frac{U_1}{U_2} = \frac{R_1}{R_2}$$

You can also write another easy-to-use formula to express U_1 as follows:

$$U_1 = R_1 \cdot \frac{U_T}{R_{EQ}} = U_T \cdot \frac{R_1}{R_1 + R_2}$$

We can conclude from both formulas that we can distribute the voltage in proportion to the resistances. In order to produce 5 V mentioned in the example, it should be dropped 5 V on one resistor, and $12-5 = 7$ V on the other. Thus, the ratio of required resistances should also be 5:7, e.g. 500 Ω and 700 Ω . This application is called **voltage divider**.

Also note that since the resulting resistance of serial connection is the sum of the individual resistances, its value will always be higher than any of the resistors replaced.

After the theoretical review, we have to make a check that the relationships we have just made are correct. Remove the power cords from our already assembled circuit and measure the resistance of each resistor and also the resulting resistance of their serial connection. In my compilation $R_1 = 99 \Omega$, $R_2 = 996 \Omega$, while the result was 1095 Ω , which is the sum of the two resistances.

Now let's build a resistor divider, which distributes the voltage at its third ($1 / (1 + 2)$), that is, it divides it between resistors in a ratio of 1:2. To do this, take two more 1 k Ω resistors and place them in the 100 Ω position as shown:

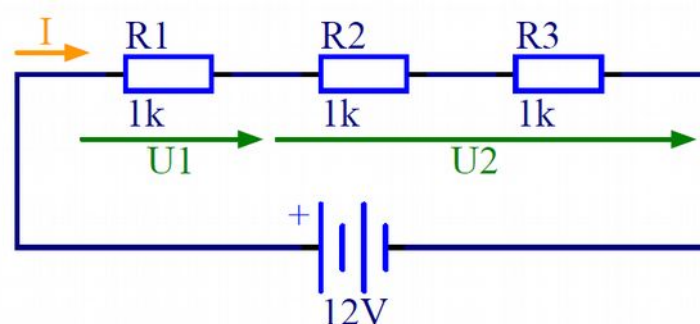


Figure 7 - Circuit, which divides the voltage at its third

Reconnect the power supply and measure U_1 and U_2 voltages! I measured $U_1 = 4.04$ V; $U_2 = 8.10$ V in case of 12.14 V supply voltage. So, the voltage at the first resistance was really about one third of the power supply:

$$\frac{12.14 \text{ [V]}}{3} = 4.0467 \text{ [V]} \approx 4.04 \text{ [V]}$$



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PARALLEL CONNECTION

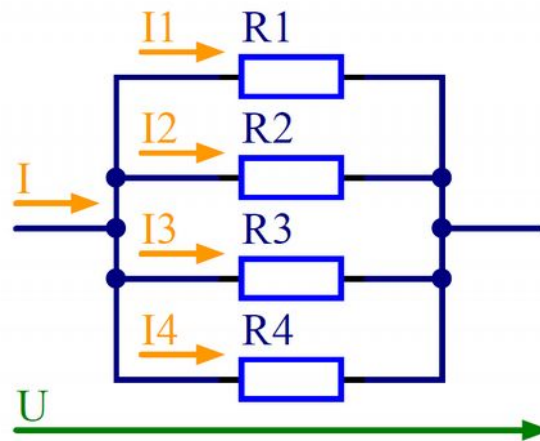


Figure 8 - Parallel connection

The resistors can be connected in a circuit not only in series but also in parallel. Even with such a connection mode, it would be good to calculate the resistance that would replace the resistors. In other words, how could the result of parallel-connected resistors be determined? It can be clearly seen that each resistor has the same voltage (U), but through each flows a different current. From Kirchhoff's first law we know that the total current in the main branch (I_e) will be equal to sum of currents in the minor branches ($I_1, I_2, I_3, I_4, \dots$):

$$I_T = I_1 + I_2 + I_3 + \dots$$

Express the individual currents from Ohm's Law:

$$I_1 = \frac{U}{R_1}$$

$$I_2 = \frac{U}{R_2}$$

$$I_3 = \frac{U}{R_2}$$

...

Then replace back:

$$I_T = \frac{U}{R_1} + \frac{U}{R_2} + \frac{U}{R_3} + \dots$$

Divide both sides by U :

$$\frac{I_T}{U} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots$$



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Finally, take the reciprocal for both sides, and notice that on the left we get the equivalent resistance:

$$R_{EQ} = \frac{U}{I_T} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots} [\Omega]$$

This formula is a bit more complicated than it was in case of the serial connection, making it more difficult to use for any resistance. It is also important to note that the resulting resistance of parallel-connected resistors will always be smaller than without interconnection.

If only two resistors are connected in parallel, then you can use the so-called “replus” formula, which is:

$$R_{EQ(1,2)} = \frac{R_1 \cdot R_2}{R_1 + R_2} [\Omega]$$

Parallel connection can be used as a current divider, but its practical significance is small, so we will not be dealing with this here.

Check the theory here also by measuring it! Connect the 100 Ω resistor and 1 k Ω in parallel! Then measure their resulting resistance without power supply, as previously learned. The instrument showed me 90.4 Ω . Replacing the previously measured values of 996 Ω and 99.3 Ω in the formula $\left(\frac{1}{996 [\Omega]} + \frac{1}{99.3 [\Omega]}\right)^{-1} = 90.29 [\Omega]$. The small difference here is also due to the inaccuracy of the measurements. Unfortunately, the connection to the 12 V power supply can not be safely connected to this, and at the end of the curriculum it will be clear why.

Assemble the following circuit:

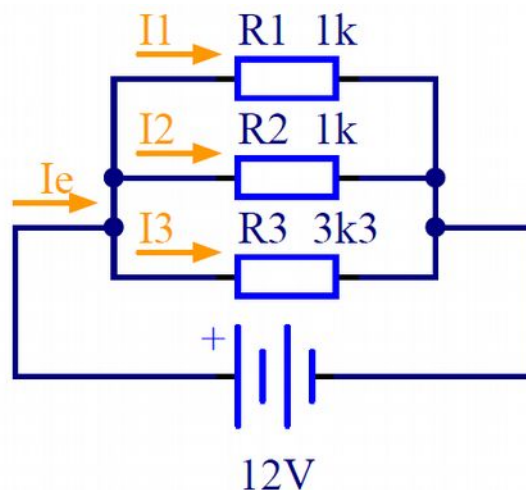


Figure 9 – An example for parallel connection

Measure the current in the main branch and in each side branch. When measuring current, take great care of where what to connect. For the sake of safety, let’s look at the following figures, which show how we can measure the currents in the main branch and in the side branches.



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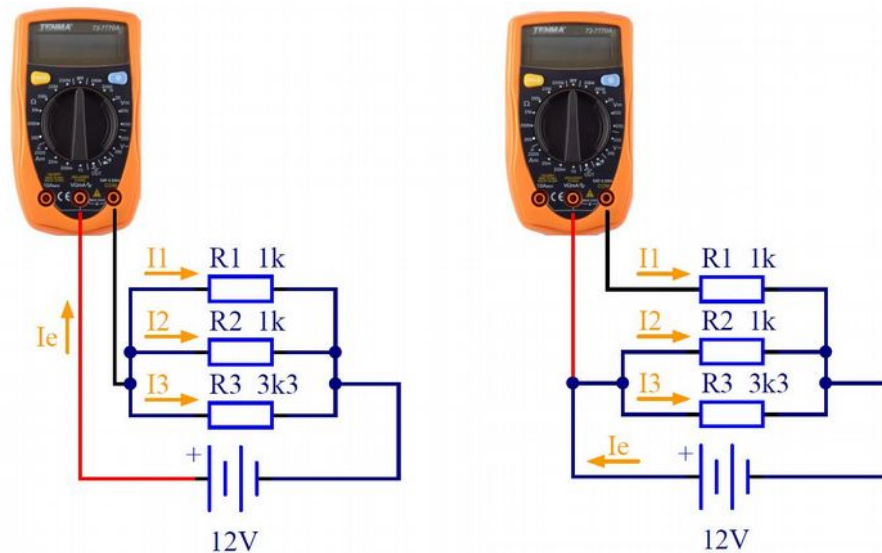


Figure 10 - Current measurement on left side in the main branch, right side in the side branch

Before we measure, estimate the highest current to be measured: the current in the main branch. First, calculate the nominal resulting resistance:

$$\frac{1}{\frac{1}{1000 [\Omega]} + \frac{1}{1000 [\Omega]} + \frac{1}{3300 [\Omega]}} = 434.2 [\Omega]$$

So, the current in the main branch: $\frac{12.14 [V]}{432.2 [\Omega]} = 0.0276 [A] = 27.6 [mA]$. So, we can feel free to use the 200 mA limit. During the measurements pay special attention and always disconnect the power supply during the conversion. Also, be careful not to short-circuit the laboratory power supply with the multimeter. The following values were shown to me:

$$I_T = 27.8 [mA]$$

$$I_1 = 11.9 [mA]$$

$$I_2 = 12.1 [mA]$$

$$I_3 = 3.7 [mA]$$

$I_1 + I_2 + I_3 = 27.7$ mA, which is approximately the current in the main branch (27.8 mA). The difference here is also due to the minor inaccuracy of the measurements.

SUMMARY FOR DETERMINING THE RESULTING RESISTANCE OF RESISTORS CONNECTED IN SERIES AND IN PARALLEL

For serial connection, the resulting resistance is always greater than the highest resistance in the chain and can be calculated as:



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$$R_{EQ,series} = R_1 + R_2 + R_3 + \dots [\Omega]$$

In case of parallel connection, the resulting resistance is always less than the lowest valued parallel connected resistor and can be calculated as:

$$R_{EQ,parallel} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots} [\Omega]$$

SIMPLIFICATION OF RESISTANCE NETWORK

In many cases, it is our task to determine the result of a composite resistor network, such as shown in the figure below.

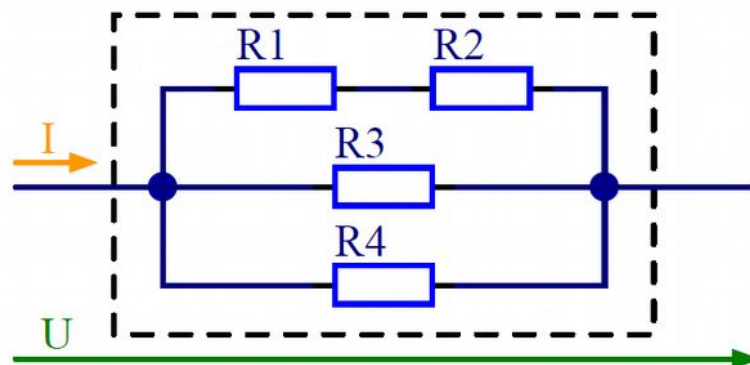


Figure 11 - Composite resistor network

At first the connection may seem complicated, but you don't have to be frightened. Most resistor networks consist of subnets of resistors connected in series and in parallel. These subnets of resistors can be stepwise merged and replaced with their resulting resistance, and sooner or later the resulting resistance of the entire resistor network can be calculated.

Let's see how it looks in practice! We can see that R_1 and R_2 are connected in series, so their resulting resistance:

$$R_{EQ1,2} = R_1 + R_2$$

If they are merged and replaced with their resulting resistance, then the resistors are connected purely in parallel.



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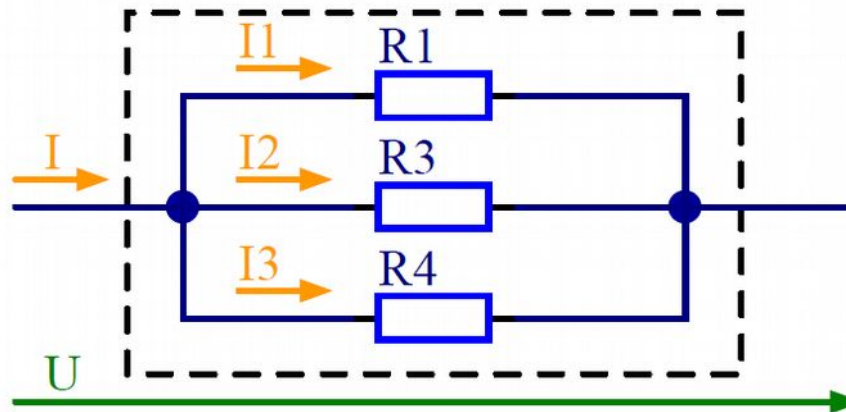


Figure 12 - The first step in simplifying a complex resistor network

The resulting resistance of the network can be determined from the correlation derived from the parallel connection:

$$R_{EQ} = \frac{1}{\frac{1}{R_{EQ1,2}} + \frac{1}{R_3} + \frac{1}{R_4}} = \frac{1}{\frac{1}{R_1 + R_2} + \frac{1}{R_3} + \frac{1}{R_4}} \quad [\Omega]$$

If you like, then set up such and similar resistor networks. Calculate and measure the resulting resistance and compare the two results.

ELECTRICAL POWER DISSIPATED ON THE RESISTOR

We haven't touched on an important question yet. I mentioned earlier that we should not connect the 12 V power supply to a resistor of just 100 Ohms. Why did I ask for this? The reason is the maximum load capacity of the resistor. This value depends on the type and design of the resistor.

The load capacity of small through-hole resistors is mainly depending on the physical size, usually between 0.25-1 W. Surface mounted, small sized resistors have a similar range, while high-performance so-called power resistors can be much larger (2 - ... 5 - 10 - W).

The resistor converts the absorbed power into heat, which causes it to heat up and transfer some of its heat to the environment. The amount of power, which can be transferred in the form of heat, depends amongst other things, on its size and the difference in temperature between the component and its environment. If its surface is small and still it is exposed to high loads, then it can only transfer this heat, if the temperature difference between the component and its environment is greatly increased. Over a given load, the component can become so hot that the resistor itself is damaged, and its properties can change, or it can even burn completely. This must be avoided!

How can we calculate, how much power is going to get to the resistance? In electrical systems, the power absorbed by a component is the product of the voltage on it, and the current flowing through it:

$$P = U \cdot I \quad [\text{W}]$$



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Fortunately, there is no need to know both the current and the voltage to calculate the power consumption of the resistors, since Ohm's Law gives the ratio of the two. Substituting $U = R \cdot I$, or $I = \frac{U}{R}$ we get the following expressions:

$$P = R \cdot I = U^2 / R$$

By observing the formula better, the following statements can be made. The power absorbed by the resistor will be proportional to the square of the current or voltage flowing through it. For example, if the voltage is doubled on the resistor, then the power is not doubled, but quadruplicated.

Let's examine what happens when we have a constant voltage power supply, but we replace the resistor. In this case, the performance increases proportionally with the reduction of the resistance (inverse proportionality). If you reduce the resistance to half, the power will be doubled.

Let's get a little back in the case of the 100 Ω resistor, when I asked, do not connect the 12V power supply onto it. In this case, the power absorbed by the resistor would be:

$$P = (12.14 [V])^2 / 100 [\Omega] = 1.47 [W]$$

The maximum allowable value for the resistor I use is only 0.6W. We should avoid overloading the resistors, since the resistance value because of the heating will certainly change, but in most cases, they will also suffer from long-term damage. Pay attention to this when using resistors smaller than 1k Ω .

If you need to convert high performance into heat, you can choose between two options. One option is to combine multiple low-power resistors, the other is the use of high-performance heating resistors manufactured for this purpose.

Let's look an example for the second solution. Build the circuit shown in the figure from a 47 Ω power resistor with a power of 5W:

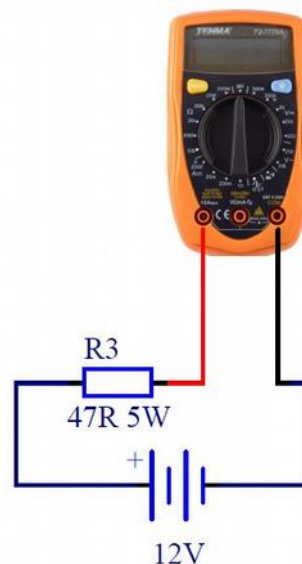


Figure 13 – Current measurement for high power resistor



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Be careful when doing this measurement, because of **the danger of burn injuries!** Before you turn on the power, always calculate how much power will get to the resistor!

$$P = U^2 / R = (12.14 \text{ [V]})^2 / 47 \text{ [\Omega]} = 3.14 \text{ [W]}$$

3.14W is less than 5W, which is allowable at this resistor, so we can turn on the circuit, but we have to calculate with the fact, that the resistor will warm up considerably. Check to see if we've put our component in a place where this may not be a problem. If it is done, we can turn on the circuit. The resistor can rise up to 100 °C in a relatively short period of time, and touching can cause burn injuries!

As a practice, measure the current but first estimate it! Expected current in this connection:

$$I = 12.14 \text{ [V]} / 47 \text{ [\Omega]} = 0.258 \text{ [A]}$$

We can notice that the current in a circuit, where the power is high, will be high, so we often have to use the previously known 10 A measurement limit for such circuits. We must do this now as well. During the measurement, the multimeter showed me 0.25 A.

SUMMARY

In this part of the curriculum, we got to know one of the most important electronic measuring instruments: the multimeter. We learned how to measure the main quantities (voltage, current, resistance). We have learned how to detect an open-circuit in our circuit. In addition, we have more in-depth knowledge about Ohm's Law, and we have investigated the characteristics of serial and parallel connection. We learned to determine the resulting resistance of a complex network. Finally, we have learned about one of the limitations of the use of resistors, their maximum power, and the method of calculation.



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