Some Experimental Solutions for Teaching Topics from the Section "Electrostatics" in the 10th Grade of the Bulgarian Secondary School

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Abstract. The study of physics in the 10th grade begins with the topics of electrostatics. The content of these topics can easily be illustrated by the students' experience related to observed electrostatic phenomena in practice and the relatively easy demonstration of the electrification of bodies. Understanding the quantities and the laws that describe the electric field, however, is very difficult for students. The reason for this is that students first begin to study the field form of matter and encounter its abstract nature. This also applies to the study of the capacitor, which has great practical importance, but it is not easy for students to understand its properties and application. All this is a reason to look for suitable methods to optimize the educational activity in the study of electrostatic phenomena. Our experience in recent years has shown that the adoption of experimental work in the educational process makes students active learners and in this particular case could facilitate the understanding of knowledge about capacitors and electric field. In this report, we have described some methodological solutions for teaching these topics, related to making a flat capacitors by students, experimental study of the charging and discharging processes of capacitors using Fourier sensors, analysis of the constructed graphical dependence between voltage and time, as well as organizing independent work to explore their practical applications. We believe that sharing this good practice can enrich physics teaching methodology and could be useful for current and future physics teachers.

Keywords: study of electrostatics and capacitors, experimental study.

1. INTRODUCTION

The topic "Electrostatics" is suitable for stimulating interest in physics and science in students as electrostatic phenomena are all around us. Each of us has felt static electricity at least once, which unfortunately sometimes could lead to dangerous accidents. Electrostatic phenomena can be easily demonstrated with a series of fun experiments - from electrified balloons, plastic balls to flying papers. Students have seen similar experiments many times, but the explanation is related to introducing the abstract concept of "electric field". The nature of the electric field and the laws which explain it could be difficult for students to understand. The topic of electrostatics in 10^{th} grade in Bulgarian school includes the study of the behavior of dielectrics in an electrostatic field and their application in capacitors. Students find it difficult to explain the operation of the capacitor, its properties and characteristics. Our experience shows that experimental work would be useful to explain the applications of capacitors, to stimulate the interest of students, making them active participants in the educational process. In this report, have been described some methodological solutions for teaching the subject related to the study, research of the properties of capacitors and their characteristics, as well as attempts to make their own ones. (In this report, we described some methodological solutions for teaching the topics related to the study of the properties of capacitors by conducting a student experimental study of their characteristics. For a deeper understanding of the principle of operation of capacitors, we conducted laboratory classes in which students constructed capacitors themselves The article describes our experience of conducting an experimental research STEM lesson that combines knowledge from different fields - mathematics and information technology, Fourier Sensors, processing results and data presentation.

2. METHODOLOGY OF THE LESSON

2. 1. Capacitor vs. battery

In the physics curriculum of the Bulgarian school, 17-year-old students are expected to study capacitors as a component of electric circuits. Students should become familiar with this device, the quantity “capacitance” and the types of capacitors. They are expected to know it is a device that stores energy, but our practice shows that this is not the case. Therefore, at the beginning of the lesson, it is necessary to explain again and more thoroughly the purpose of the capacitor.

For this lesson, we have applied methodical approaches to show the differences and similarities between a capacitor and a battery. We set the students the following tasks: 1. to connect an electric circuit in which there is a capacitor and a battery - position 1. And then 2.

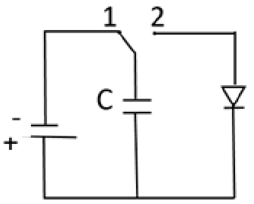

Fig. 1 An electrical circuit to analyze the similarities and differences between a capacitor and a battery.

Students describe their observations by completing a worksheet. Both devices store energy for later use. However, the capacitor is a passive device - it only stores or releases electrical energy, while the battery is an active device - it converts chemical energy into electrical energy, and then electrical energy into thermal, light, mechanical. The capacitor charges quickly (between 1 and 10 seconds), while the battery much more slowly (from a few minutes to an hour). Students can make a comparison by analyzing how long it takes to charge a phone battery. The capacitor discharges quickly, then the voltage drops sharply and the diode eventually stops working. The battery reverses its polarity when charging and discharging. The polarity of the capacitor is the same when charging and discharging - this can easily be checked by the light of the diode. As a result, students can conclude that a capacitor cannot work as a battery.

2. 2. Charging and discharging a capacitor

After observing that the capacitor charges and discharges rapidly, the question that arises is - how long the capacitor charges and discharges? When the switch is turned to position 1 (Fig. 2a), the capacitor is charged. In position 2, the capacitor is discharged and the voltage variation as a function of time is recorded. The charging and discharging times are determined experimentally. This practical work is usually part of university courses (Stavnisty, N. N., 2017), although there are examples of using simple setups and home experiments with smartphones (Hurtado-Gutierrez R. and Tejero A., 2023). Fourier sensors (Fig. 2b) are used to measure voltage and current. The results are presented as tables and graphs - voltage and current as a function of time.

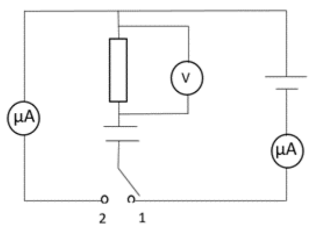

Fig. 2a) Electric circuit for the study of the charging and discharging time of a capacitor.

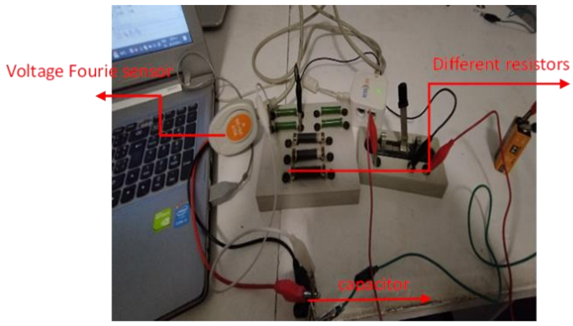

Fig. 2b) Experimental setup to determine the rate of charging and discharging of a capacitor and what it depends on.

With a powerful source with no internal resistance and ideal conductors, the ideal capacitor would charge instantaneously. In reality, the charging and discharging time depends on the capacitance of the capacitor and the resistance in the circuit. An additional resistance is included in the circuit, making the charging time actually measurable. Since 9th grade, students know Ohm's law for the entire circuit (1):

$$\varepsilon = IR = U_C \quad (1)$$

Using expressions for current $I = \frac{\Delta q}{\Delta t}$ and capacity $C = \frac{q}{U}$ we obtain *emf* in the circuit:

$$\varepsilon = \frac{\Delta q}{\Delta t} R + \frac{q}{C} \quad (2)$$

We get the rate of change of charge on the plates of the capacitor (3) and change of voltage (4), i. e. the charging speed:

$$\frac{\Delta q}{\Delta t} + \frac{q}{RC} = \frac{\varepsilon}{R} \quad (3)$$

$$\frac{\Delta U}{\Delta t} + \frac{U}{RC} = \frac{\varepsilon}{RC} \quad (4)$$

Although the 10th grade students cannot solve these equations, they show that the charging rate depends on the resistance of the circuit R and the capacitance of the capacitor C. What can be done is for the students to check experimentally how the time for charging depends on these two quantities. A characteristic time constant (5) is introduced:

$$\tau = RC \quad (5)$$

This time constant is related to the fact that the charging and discharging processes are not instantaneous, but occur at a finite rate (Senamaw, M. Z., 2019). The time constant indicates how long after the start of the voltage it has reached (1-e^{-1}), i. e. 63.2 % of the final value, and during discharge - for how long the voltage decreased $e = 2{,}71$ times (Serway, R. A and Vuille, C., 2010). The capacitor is assumed to be fully charged after time 5τ. In the profiled preparation in 11th grade, the meaning of these dependencies can be considered in more detail - exponential increase and decrease of current and voltage.

3. EXPERIMENTAL DETERMINATION OF CHARGING AND DISCHARGING TIME OF CAPACITOR

For experimental determination of the charging and discharging time, ready-made electrolytic capacitors of different capacities are first used for example – 2 μF, 250 μF, 1000 μF. Different resistances are also used – 1000 Ω, 2000 Ω, 5000 Ω. Fig. 3 shows the voltage variation as a function of time for a capacitor with a capacitance of 1000 μF and a circuit resistance of 1 kΩ.

By using the graph the time constant is experimentally determined - the time for which the voltage value increases to 63.2 % of the maximum (Fig. 4).

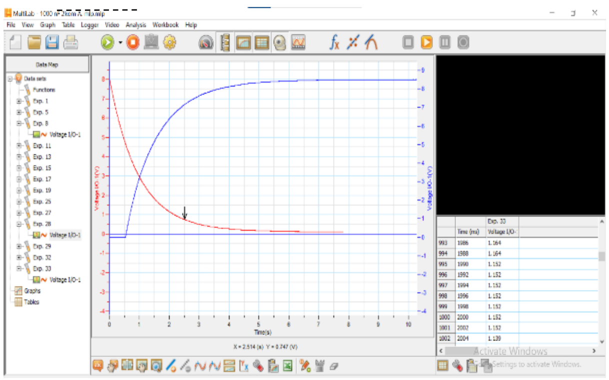

Fig. 3 The change in voltage when charging (blue) and when discharging (red).

The theoretical value of the time constant is 2 s, the actual value obtained is 1.626 s. The voltage values after time 2τ, 3τ, 4τ and 5τ are determined from the graphs. Table 1 presents experimentally determined and theoretically calculated results for charging a capacitor with a capacity of 1000 μF and a resistor with a resistance of 1000 kΩ. Table 2 presents experimental and theoretical data for discharging the same capacitor.

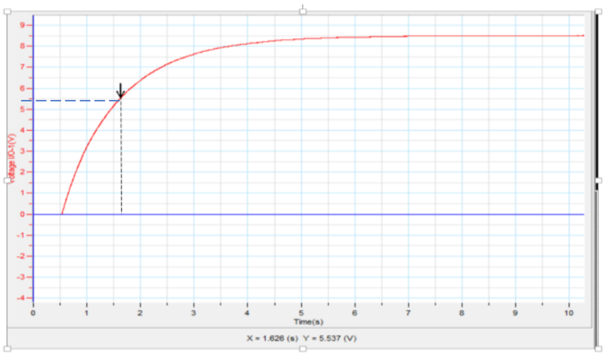

Fig. 4 Experimental determination of the time constant.

TABLE 1. Voltage value when charging a capacitor.

τ, s	%, charge	U_c, V Theoretical	U_c, V Experimental
1	63,2	5,402	5,365
2	86,2	7,368	7.318
3	95,0	8,121	8,065
4	98,2	8,394	8,336
5	99,3	8,548	8,489

TABLE 2 Voltage value when discharging a capacitor

τ, s	%, charge	U_c, V Theoretical	U_c, V Experimental
1	36,8	5,402	5,365
2	13,5	7,368	7.318
3	5,0	8,121	8,065
4	1,8	8,394	8,336
5	0,7	8,548	8,489

During the lesson the reasons for the differences are discussed - presence of additional resistances; the capacity of the capacitor is different from the instructions on the housing. As a different variant of this task, the capacitance of a capacitor can be determined from the experimental value, if it is not known. The time constant is also determined by the discharging time (Fig. 5).

The two results are then compared. The students make a conclusion about the parameters which the charging and discharging time depends on.

Charging and discharging time graphs are constructed as a function of capacitor capacitance and circuit resistance. Students can get to the conclusion that the relationships are linear. By using the graphs, it is found that the discharge process is much faster than the charge process.

The reason for this is that the voltage source is not ideal, it has internal resistance, and this increases the charging time.

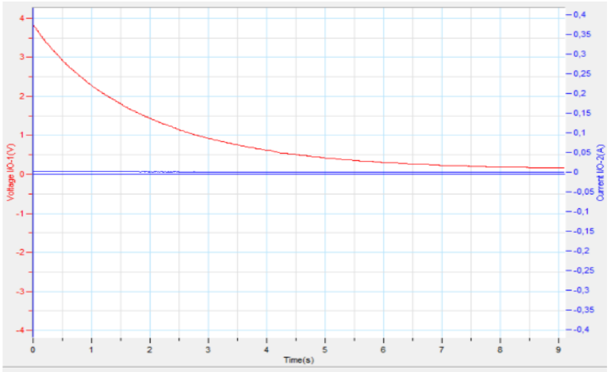

Fig. 5 Capacitor voltage drop as a function of time.

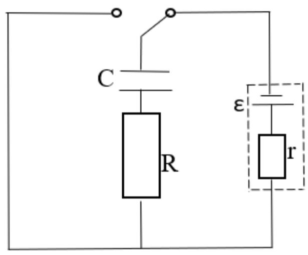

Fig. 6 The internal resistance of the source increases the charging time of the capacitor.

Students are asked to consider the question - What does the voltage value marked on the capacitor case mean?

By applying an increasing voltage, it is found that above a certain value breakdown occurs. Physics classrooms in schools do not have high voltage sources, so an electrostatic machine can be used for this purpose. This experiment can be done with a homemade capacitor (Fig. 7) from two sheets of aluminum foil sandwiched between laminating foil.

When the breakdown voltage is reached, sparks appear.

When reaching a value of the order of 50-60 V, crackling begins, sparks appear and the aluminum breaks through in some places. Thus, it is established that the voltage marked on the capacitor case is the maximum at which the capacitor operates.

Fig. 7 Experiment to determine the breakdown voltage.

4. STUDY OF SELF-MADE CAPACITORS

Flat capacitors are easiest to make. In the program for 10th grade, the dependence of the capacity of a flat capacitor on the area of the plates and the distance between them is discussed. This dependence can be experimentally investigated. Each group of students makes a different type of capacitor - with different area sizes of aluminum foil plates (Fig. 8a), including rolled ones (Fig. 8 b), different numbers of paper sheets as a dielectric, or different numbers of laminating foils as a dielectric (Fig. 8c).

Comparison of theoretically calculated capacitance values with experimentally measured ones. For example, for a capacitance with a theoretical value of 33 nF, the measured experimental value is 26,5 nF. The values of the capacities of such self-made capacitors are relatively small - on the order of 2.5 nF to 26,5 nF. These small values require large resistances (on the order of MΩ) for obtaining a real measurable charging and discharging time.

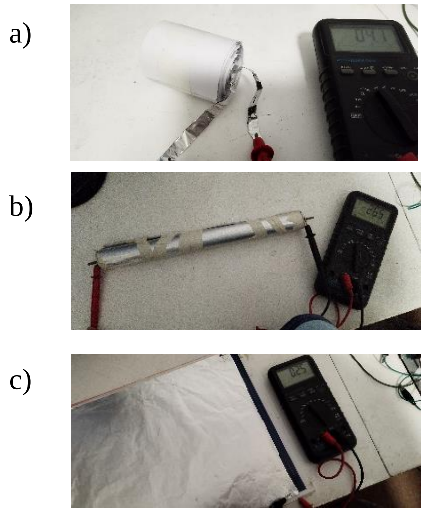

Fig. 8 Images of self made capacitors.

a) Paper capacitor with aluminum foil plates; b) capacitor with laminating foil as dielectric and big area of plates; c) aluminum plates with laminating foil as dielectric.

5. ELECTROSTATIC FIELD OF FLAT CAPACITOR

To give students an idea of electrostatic field, a flat capacitor with two long plates immersed in a liquid dielectric (such as oil or engine oil) can be considered. When a voltage is applied, the homogeneous electric field can be visualized by potassium permanganate crystals in the liquid (Fig. 9). The field is homogeneous if the distance between the plates is much smaller than their length. Each of the plates is considered as infinite. The fields are offset outside the plates and the field is between the plates.

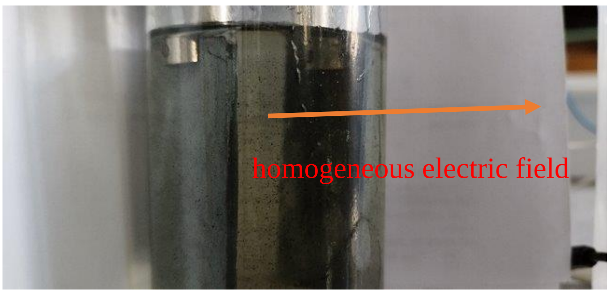

Fig. 9 Visualization of electric field of flat capacitor – parallel lines of potassium permanganate crystals could be seen between metal plates.

6. CONCLUSIONS

The experimental and inquiry work carried out contributes to the understanding of the concepts of charging and discharging of a capacitor and capacity of the capacitor. The experience of self-made capacitors makes students active participants in the learning process. So they can check for themselves what it means to charge and discharge the capacitor, understand the place of the dielectric in the capacitor, how the area and the distance between the plates affect the capacity. Using research methods, the time of charging and discharging a capacitor is determined, the linear dependence of this time on resistance and capacity is determined experimentally. It is experimentally found that the charging time is greater than the discharging time and the reason for this is internal resistance of the battery. Thus once again the dependence of the charging time on the resistance is understood. The self made capacitors have many defects as one of them being poor insulation - between the individual dielectric layers and between the dielectric and the plates, these air layers change the dielectric constant and therefore the capacitance.

We believe that the good practice described in this article will be useful to secondary school physics teachers. Teaching through experimental problem solving has great cognitive potential and is a promising way to implement STEM learning in the classroom.

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