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Charging and Discharging a Capacitor through a DC Circuit: "PHET" Demonstration and Data Analysis

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Abstract

"PHET" simulator was an excellent remote-teaching tool during the "COVID-19" pandemic times. In this article, we use this simulator to demonstrate the charging and discharging processes of a capacitor via a DC circuit. A simple circuit consists of a battery, a resistor and a capacitor is exploited to explain the charging process by converting the battery's voltage into a stored electric energy inside the capacitor. After the full charging of the capacitor, the battery is removed and the stored energy is allowed to discharge through a resistive load. During both processes of charging and discharging, it is available to record the voltage across the capacitor and/or across the resistor as functions of time. Then, these values are used to obtain other related, to the capacitor, quantities. This work is appointed to the students at the early university levels in the faculties of science and engineering who have some difficulties to understand the basics of this experiment. Almost, the difficulties are due to the brief derivations of the principal equations in the physics textbooks. Therefore, detailed derivations of the whole relevant mathematical relations are presented, in this article, and are correlated to the generated results in this work. The evaluation of the simulated experiment and the detailed mathematical derivations as well as analyzing the obtained data would serve the deep understanding of the targeted experiment's aims.

Keywords: Capacitor, Charging, Discharging, Time constant, PHET simulation.

Introduction

Due to the interruption of study in schools and universities during the years of the "COVID-19" pandemic, many teachers and demonstrators all over the world gave more attentions to the on-line remote-teaching tools. It is observed that different educational platforms have enabled their resources and joining the webinars was encouraged (Babinčáková and Bernard 2020; "https://phet.colorado.edu/"; "http://www.algodoo.com/"). Indeed, simulated experiments and virtual laboratories have played excellent roles in delivering deep scientific meanings and concepts to the remote learners (Babinčáková and Bernard 2020; Coramik and Özdemir 2021; de Berredo-

Peixoto et al. 2018; Özdemir and Coramik 2021; Velloso et al. 2021).

A physics virtual laboratory can be effectively utilized to demonstrate physics experiments to the leaners. This can be achieved by operating some well-designed interactive simulators such as those produced by "PHET" ("https://phet.colorado.edu/"). The "PhET" project aims to make all students and teachers having access to their open resources of intuitive, exploratory and easy-to-use educational simulations which are available in different languages (Moore 2016). These effective simulations can be either operated online or offline after downloading into the computers. Interestingly, they can be operated even using the smartphones!

It was a good opportunity to teach some concepts related to the charging and discharging processes of a capacitor to our students where many of them had confusion how the capacitor stores electric energy and how the voltages and the current in the electric circuit behave. The used simulation from PHET is the "Circuit-construction-kit-ac-virtual-lab" ("https://phet.colorado.edu/sims/html/circuit-construction-kit-ac-virtual-lab/latest/circuit-construction-kit-ac-virtual-lab_en.html"). It is used to demonstrate both the charging and the discharging processes of a capacitor as well as the determination of the time constant value of the simulated apparatus. Moreover, detailed derivation of the whole relevant mathematical relations are presented and correlated to the generated results. These simple and organized derivations are supposed to be helpful for the students who study physics at the early university levels. Also, the students will be able to correlate the different concepts related to this kind of experiments and performing the analyses of the experimental data effectively.

Theoretical considerations

A capacitor is mainly consisting of two conducting surfaces which are separated by an insulating (dielectric) layer. The two conducting surfaces could be either rectangular plates or in the form of concentric spheres or concentric cylinders (Floyd 2009; Radi and Rasmussen 2013; Serway and Vuille 2012; Theraja et al. 2010). The main purpose of the capacitor is storing the electric energy as an electrostatic field in the dielectric medium through a process called "charging of the capacitor" (de Berredo-Peixoto et al. 2018; Floyd 2009; Radi and Rasmussen 2013; Salgueiro da Silva and Seixas 2013; Serway and Vuille 2012; Theraja et al. 2010). If this electrostatic field collapses, the stored energy is released through the loads of the electric circuit in a process known as "discharging of the capacitor". The capacitor has a characteristic property called the capacitance (C) and its measuring unit is the "Farad" (Theraja et al. 2010). A capacitor's capacitance is defined as "the amount of charge (Q) required to create a unit potential difference (V) between the capacitor's plates" as expressed by equation (1). Basically, the capacitance of a capacitor depends on the geometrical parameters of the conducting surfaces as well as the dielectric constant of the insulating material which is sandwiched between these two surfaces.

$$C = \frac{Q}{V} \quad (1)$$

Regarding the practical applications of capacitors, they can be found in digital control circuits, power supply filters, timing circuits, etc. (Floyd 2009; Radi and Rasmussen 2013; Serway and Vuille 2012; Theraja et al. 2010). So, it is so important for any student, studying physics, to know how a capacitor works and how it behaves in different electric circuits and networks.

Charging process of a capacitor through a DC circuit

By connecting a DC voltage source to a capacitor connected in series with a resistive load for the purpose of charging the capacitor, the voltage across the capacitor (V_C) doesn't instantaneously reach its maximum value. It rather grows in an exponential manner until the full charging of the capacitor. This is due to the exponential decrease of the circuit's current from a maximum value until reaching zero at the full charging of the capacitor. Therefore, the fully charged capacitor is known to block the DC current flowing (Theraja et al. 2010).

In order to know how the charging process takes place, assume an uncharged capacitor is connected in a circuit as shown in figure (1). Once the electric switch (S) is closed, the current (I) in the circuit has its maximum value (I_o) which equals V_O/R from Ohm's law; V_O is the source's voltage and R is the resistance of the in-series connected fixed load resistor. This is due to that the capacitor is uncharged and it doesn't store any charge; i.e., $Q = 0$. Consequently, V_C equals zero at this moment. Afterwards, the charges begin to flow in the circuit causing an electric current and the capacitor, then, starts its charging process. With time, the plates of the capacitor are being charged and the potential difference across the capacitor as a function of time ($V_C(t)$) increases. By applying Kirchhoff's voltage law (KVL) to analyze this circuit, one finds that:

$$V_O - V_R(t) - V_C(t) = 0 \qquad (2)$$

or,

$$V_O - RI(t) - \frac{Q(t)}{C} = 0 \qquad (3)$$

At the beginning of charging (t = 0 (s)) and since the capacitor is initially uncharged, the charge Q (t = 0 s) on the capacitor's plate equals zero and I (t = 0 s) = I_O. So, equation (3) leads to:

$$V_O - I_O R = 0 \qquad \text{at } t = 0 \text{ s} \qquad (4)$$

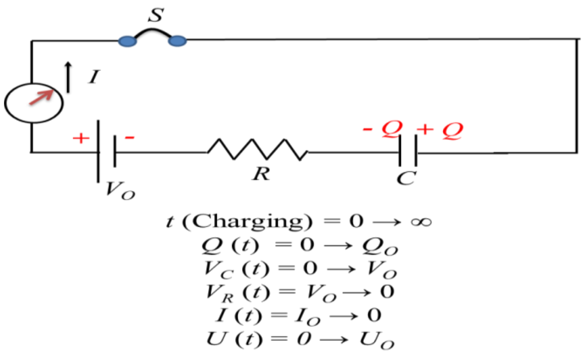


Figure (1): A schematic diagram shows the charging process of a capacitor through a DC circuit.

On the other hand, when the capacitor is fully charged (i.e., $t \to \infty$), Q reaches its maximum value Q_O (which equals CV_O) while I tends to zero at that moment. This can be explained by studying the variation of current with the time of charging of the capacitor which is expressed as:

$$I(t) = \frac{dQ(t)}{dt} \qquad (5)$$

In this case, equation (3) can be rewritten as follows:

$$RI(t) + \frac{\int I(t)dt}{C} = V_O \qquad (6)$$

By differentiating equation (6) with respect to t, one obtains:

$$R\frac{dI(t)}{dt} = -\frac{I(t)}{C} \qquad (7)$$

A rearrangement of equation (7) yields:

$$\frac{dI(t)}{I(t)} = -\frac{dt}{RC} \qquad (8)$$

The integration of both sides of equation (8) gives:

$$ln\,(I(t)) = -\frac{t}{RC} + k_1 \qquad (9)$$

where, k_1 is the constant of integration. It can be determined from the initial conditions where $I = I_O$ (Ampere) at t = 0 (s). So, by substituting into equation (9), k_1 is given as:

$$k_1 = ln\,(I_O) \qquad (10)$$

then, equation (9) leads to:

$$ln\left(\frac{I(t)}{I_O}\right) = -\frac{t}{RC} \qquad (11)$$

or,

$$I(t) = I_O e^{-\frac{t}{RC}} \qquad (12)$$

This equation describes the behavior of the electric current in the circuit during the charging process where it starts from its maximum value I_O (Ampere) at t = 0 s. Then, it exponentially decreases until reaching zero at the full charging of the capacitor.

Now, the amount of charge Q deposited on the capacitor's plate can be determined by substituting equation (12) into equation (5) and replacing ($I_O RC$) by (Q_O).

$$Q(t) = -Q_O e^{-\frac{t}{RC}} + k_2 \qquad (13)$$

where, k_2 is the constant of integration. It can be determined from the initial conditions where $Q = 0$ (Coulomb) at t = 0 (s). So, by substituting into equation (13), k_2 is given as:

$$k_2 = Q_O \qquad (14)$$

then, equation (13) leads to:

$$Q(t) = Q_O\left(1 - e^{-\frac{t}{RC}}\right) \qquad (15)$$

By dividing equation (15) onto the capacitance's value (C) (from equation (1)), the voltage across the capacitor during the charging process ($V_C(t)$) can be obtained.

$$V_C(t) = V_O\left(1 - e^{-\frac{t}{RC}}\right) \qquad (16)$$

So, the corresponding voltage across the resistor (from equation (2)) is given as:

$$V_R(t) = V_O - V_C(t) = V_O e^{-\frac{t}{RC}} \qquad (17)$$

Equations (15 and 16) show that both Q and V_C increase during the charging process of the capacitor. Also, it can be realized that $Q = Q_O$ (Coulomb) and $V_C = V_O$ (Volt) at the full charging of the capacitor. On the other hand, $V_R(t)$ (i.e., equation (17)) has the same behavior of the electric current flowing described by equation (12), where $V_R(t) = RI(t)$.

Regarding the electrostatic potential energy (U_O) stored in the capacitor; it can be expressed as the work done (W) by the battery. In order to charge a capacitor from a charge $Q = 0$ (Coulomb) to a final charge $Q = Q_O$ (Coulomb), the electric work is given as (Floyd 2009; Radi and Rasmussen 2013; Serway and Vuille 2012; Theraja et al. 2010):

$$W = U_o = \int_0^{Q_O} \frac{Q}{C} dQ = \frac{(Q_O)^2}{2C} \quad (18)$$

But, to charge the capacitor to any value $Q(t)$ during the charging process, W and hence U, as a function of the time can be rewritten as:

$$W(t) = U(t) = \frac{1}{2}\frac{(Q(t))^2}{C} \quad (19)$$

which also, equals $\left(\frac{1}{2}Q(t)V_C(t)\right)$ or $\left(\frac{1}{2}C\left(V_C(t)\right)^2\right)$ or $\left(\frac{1}{2}C\left(V_O - V_R(t)\right)^2\right)$.

Equations (12, 15, 16, 17 and 19) are the potential equations describing the charging process of the capacitor through a DC circuit.

Discharging process of a capacitor through a DC circuit

As the battery is removed from the circuit and the capacitor is allowed to discharge its stored charges through the connected resistive load as shown in figure (2), the electric current flows in a direction which is opposite to that of the charging current (Theraja et al. 2010). Therefore, the following relation is verified:

$$V_R(t) = -V_C(t) \Rightarrow RI(t) = -\frac{Q(t)}{C} \quad (20)$$

or,

$$R\frac{dQ(t)}{dt} = -\frac{Q(t)}{C} \quad (21)$$

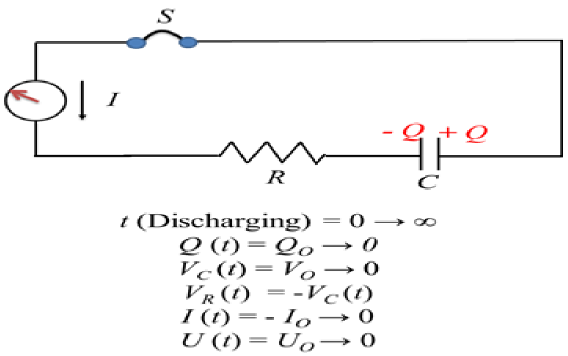


Figure (2): A schematic diagram shows the discharging process of a capacitor through a DC circuit.

A rearrangement of equation (21) yields:

$$\frac{dQ(t)}{Q(t)} = -\frac{dt}{RC} \quad (22)$$

The integration of both sides of equation (22) gives:

$$ln\,(Q(t)) = -\frac{t}{RC} + k_3 \quad (23)$$

where, k_3 is the constant of integration. It can be determined from the initial conditions where $Q = Q_O$ (Coulomb) at the beginning of discharge (i.e., $t = 0$ (s)). So, by substituting into equation (23), k_3 is given as:

$$k_3 = ln\,(Q_O) \quad (24)$$

then, equation (23) leads to:

$$ln\,(Q(t)) = -\frac{t}{RC} + ln\,(Q_O) \quad (25)$$

or,

$$ln\left(\frac{Q(t)}{Q_O}\right) = -\frac{t}{RC} \quad (26)$$

which gives:

$$Q(t) = Q_O e^{-\frac{t}{RC}} \quad (27)$$

The voltage across the capacitor during the discharging process ($V_C(t)$) can be obtained as follows:

$$V_C(t) = \frac{Q(t)}{C} = V_O e^{-\frac{t}{RC}} \quad (28)$$

By referring to equation (20), the corresponding voltage across the resistor, during the discharging process, is given as:

$$V_R(t) = -V_C(t) = -V_O e^{-\frac{t}{RC}} \quad (29)$$

Now, it is easy to obtain the discharging current, where:

$$I(t) = \frac{V_R(t)}{R} = -\frac{V_O}{R}e^{-\frac{t}{RC}} = -I_O e^{-\frac{t}{RC}} \quad (30)$$

This equation can be, also, obtained from the differentiation of equation (27) with respect to t.

Since the capacitor releases its charge during the discharging process, the stored electrostatic potential energy is decreased according to the following equation:

$$U(t) = \frac{(Q(t))^2}{2C} \quad (31)$$

which also, equals $\left(\frac{1}{2}Q(t)V_C(t)\right)$ or $\left(\frac{1}{2}C\left(V_C(t)\right)^2\right)$ or $\left(\frac{1}{2}C\left(-V_R(t)\right)^2\right)$.

Equations (27-31) show that Q, V_C, V_R, I and U have an exponential decay behavior during the discharging process and all of them are ultimately reaching zero at the full discharging of the capacitor. Also, these five equations are considered the potential equations describing the discharging process of the capacitor through a fixed resistive load.

Time constant (λ)

Now, it is known that there are two sets of principal equations which are completely describing the charging and discharging processes of the capacitor. All of these equations contain the term (*RC*) which is called the time constant (measured in seconds) and, commonly, has the symbol (*λ*) (Floyd 2009; Radi and Rasmussen 2013; Serway and Vuille 2012; Theraja et al. 2010). So, *λ* can be defined from each one of these equations. All these possible definitions of *λ* are included in table (1). Additionally, by referring to any of the principal equations in both processes of charging and discharging of the capacitor, one finds that the term ($e^{-t/RC}$) tends to 0.007 if t = 5*λ*. It means that at a time of charging equals 5*λ*, the capacitor is charged by more than 99 % of its maximum capacity while it loses more than 99 % of the maximum charge at a time of discharging equals 5*λ*.

Table 1. Different possible definitions of the time constant (*λ*).

Process	Equation	*λ*- definition
Charging	12	The time (*t*) of charging when the electric current (*I*) in the circuit reaches 37 % of its maximum value (I_O) (i.e., when *I* (*t*) loses 63 % of its maximum value (I_O)).
	15	The time (*t*) of charging when the charge (*Q*) on the capacitor's plate reaches 63 % of its maximum value (Q_O).
	16	The time (*t*) of charging when the voltage on the capacitor (V_C) reaches 63 % of its maximum value (V_O).
	17	The time (*t*) of charging when the voltage on the resistor (V_R) reaches 37 % of its maximum value (V_O).
Discharging	27	The time (*t*) of discharging when the charge (*Q*) on the capacitor's plate reaches 37 % of its maximum value (Q_O) (i.e., when *Q* (*t*) loses 63 % of its maximum value (Q_O)).
	28	The time (*t*) of discharging when the voltage on the capacitor (V_C) reaches 37 % of its maximum value (V_O) (i.e., when V_C (*t*) loses 63 % of its maximum value (V_O)).
	29	The time (*t*) of discharging when the voltage on the resistor (V_R) reaches (- 37) % of the maximum value (V_O).
	30	The time (*t*) of discharging when the electric current (*I*) in the circuit reaches 37 % of its maximum value (I_O) (i.e., when *I* (*t*) loses 63 % of its maximum value (I_O)).

Virtual laboratory using a "PHET" simulator

In the presented work, the PHET simulation "Circuit-construction-kit-ac-virtual-lab" ("https://phet.colorado.edu/sims/html/circuit-construction-kit-ac-virtual-lab/latest/circuit-construction-kit-ac-virtual-lab_en.html") is used to demonstrate the charging an discharging processes of a capacitor. The following conditions are chosen; R = 100 Ω, C = 0.20 F and VO = 5, 10 and 15 V. So, the time constant (λ = RC) is assumed to be 20 s. Moreover, the resistances of both the DC source and the connection wires are considered zero where they can be controlled by the user.

One can realize that the whole experiment and its calculations can be implemented using only one measuring device, e.g. a voltmeter. However, two voltmeters to measure both VC (t) and VR (t) are used in this simulation. Then, the electric current can be determined by dividing (VR (t)) onto (R).

Charging process

Figure (3) represents a screenshot showing the charging process at the time of charging 20 s (i.e., 1 λ) when VO = 10 V. The voltages on the capacitor and the resistor, at this time, are 6.33 V and 3.67 V, respectively. These two values correspond ~ 63 % of VO and ~ 37% of VO, respectively

Discharging process

Figure (4) represents a screenshot showing the discharging process at the time of charging 20 s (i.e., 1 *λ*). The voltages on the capacitor and the resistor, at this time, are 3.67 V and - 3.67 V, respectively. These two values correspond ~ 37 % of V_O and ~ (- 37) % of V_O, respectively.

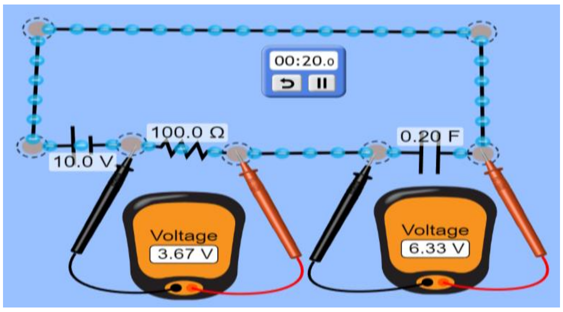


Figure (3): A screenshot shows the charging process of the capacitor at time of charging 20 s; V_O = 10 V, R = 100 Ω and C = 0.20 F ("https://phet.colorado.edu/sims/html/circuit-construction-kit-ac-virtual-lab/latest/circuit-construction-kit-ac-virtual-lab_en.html").

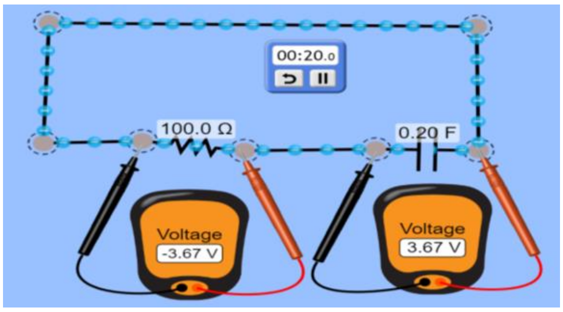


Figure (4): A screenshot shows the discharging process of the capacitor at time of discharging 20 s; R = 100 Ω and C = 0.20 F ("https://phet.colorado.edu/sims/html/circuit-construction-kit-ac-virtual-lab/latest/circuit-construction-kit-ac-virtual-lab_en.html")

Results and discussion

Charging process

Figure (5-a) shows the V_C (t) charging curves for the values of V_O = (5, 10 and 15) V. All these cases have the same behavior of increasing V_C exponentially with the time of charging according to equation (16). Also, all of them exceed 99 % of their maxima at 100 s which equals 5λ. The values of V_C at time 5λ of charging are marked on the curves. Moreover, the corresponding graphs of the voltage across the resistor, V_R (t) given by equation (17), are shown in figure (5-b). For all V_R (t) curves, V_R loses more than 99 % of its maximum value during the first 5λ.

The Q (t) graphs during the charging process can be estimated from the plotted curves in figure (5-a) by multiplying the values of V_C(t) by C, see figure (6). For all Q (t) curves, Q exceeds more than 99 % of its maximum value during the first 5λ.

Also, the graphs of the circuit's current during the charging process are plotted based on equation (12), see figure (7). For all I (t) curves, I loses more than 99 % of its maximum value during the first 5λ.

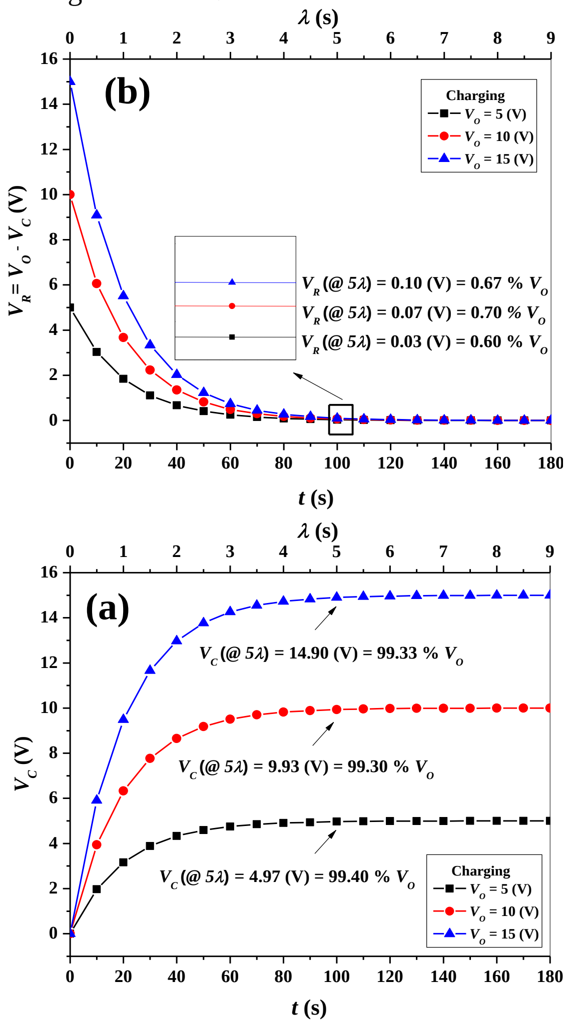


Figure (5): (a) V_C (t) and (b) V_R (t) graphs during the charging process of the capacitor for three different values of V_O.

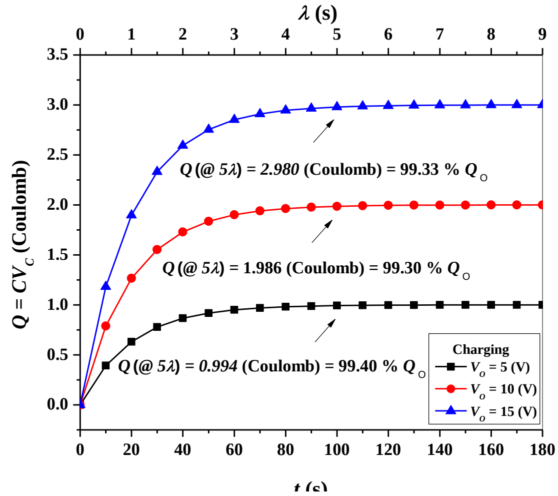


Figure (6): Q (t) graphs during the charging process of the capacitor for three different values of V_O.

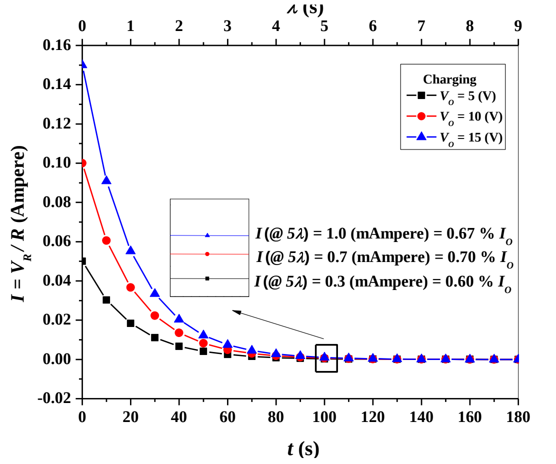


Figure (7): $I\,(t)$ graphs during the charging process of the capacitor for three different values of V_O.

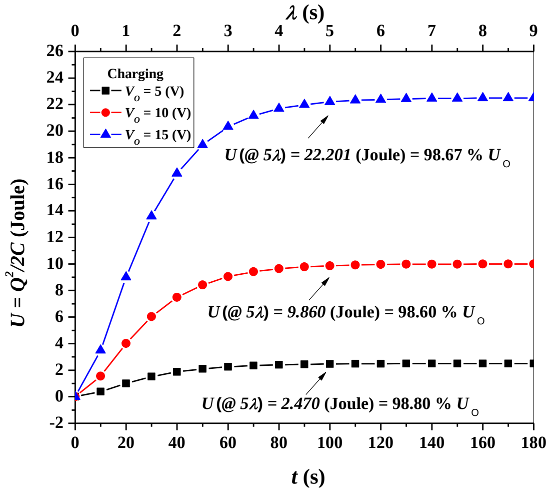


Figure (8): $U\,(t)$ graphs during the charging process of the capacitor for three different values of V_O.

Discharging process

Figure (9-a) shows $V_C\,(t)$ discharging curves for the values of V_O = (5, 10 and 15) V. The three curves have the same behavior of exponential decaying with increasing the time of discharging according to equation (28). Also, all of them lost more than 99% of their initial values (maxima) after 100 s (i.e., 5λ). The values of V_C at time 5λ of discharging are marked on the curves. Moreover, the graphs of the voltage across the resistor, $V_R\,(t)$ given by equation (29), are shown in figure (9-b).

The $Q\,(t)$ graphs during the discharging process can be estimated from the plotted curves in figure (9-a) by multiplying the values of $V_C\,(t)$ by C, see figure (10).Also, the graphs of the circuit's electric current $I(t)$ during the discharging process are plotted based on equation (30), see figure (10).

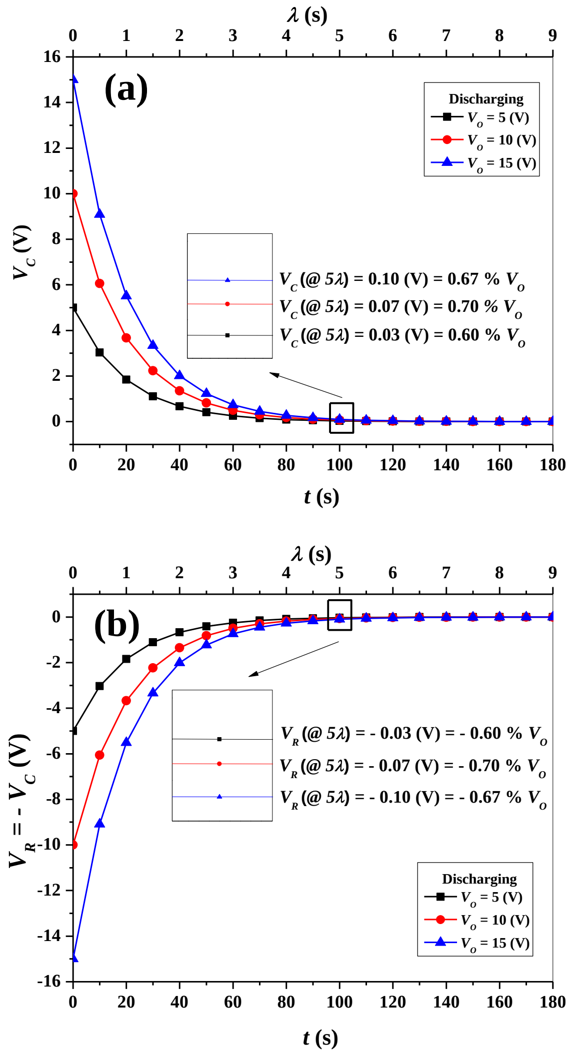


Figure (9): (a) $V_C\,(t)$ and (b) $V_R\,(t)$ graphs during the discharging process of the capacitor for three different values of V_O.

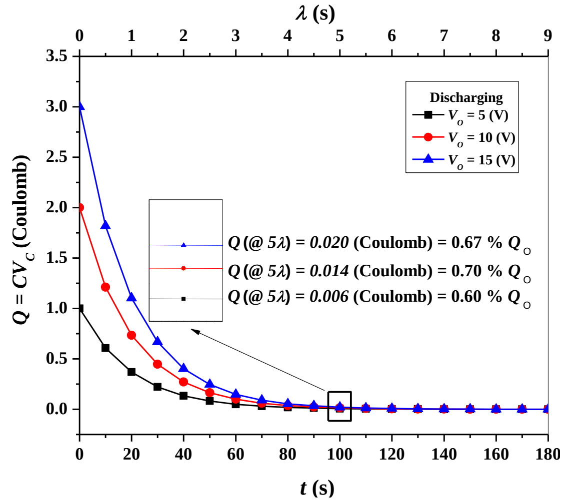


Figure (10): $Q\,(t)$ graphs during the discharging process of the capacitor for three different values of V_O.

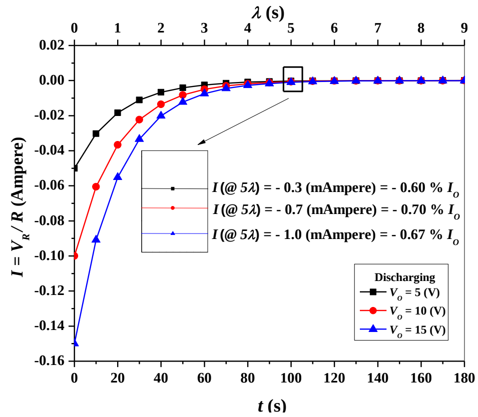


Figure (11): *I* (*t*) graphs during the discharging process of the capacitor for three different values of V_O.

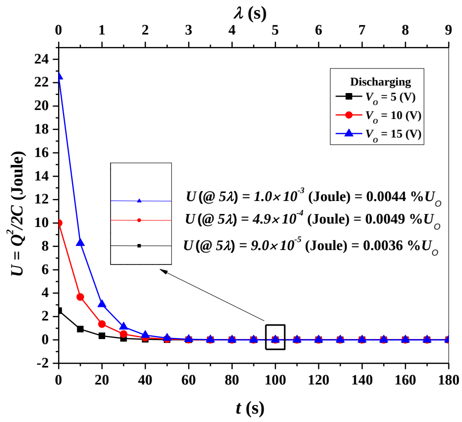


Figure (12): *U* (*t*) graphs during the discharging process of the capacitor for three different values of

Time constant determination

In order to determine the time constant, the exponential term in any of the principal equations can be transformed into a linear behavior. Let's apply this on only one of these equations; say equation (12). By taking the (*ln*) of both sides of this equation, it becomes a straight line equation as follows (Salgueiro da Silva and Seixas 2013):

$$ln(I(t)) = ln\,(I_O) - \frac{1}{RC}t \qquad (32)$$

By plotting the relation between *ln* (*I*(*t*)) versus *t* (in case of charging) for the three different values of V_O, three straight lines are obtained as shown in figure (13). By fitting each line data by a linear fitting, the intercepts and the slopes (which represent the reciprocal of the time constant values) can be determined, see table (2). Obviously, λ doesn't depend on V_O value but, it always equals the multiplication product of *R* and *C*.

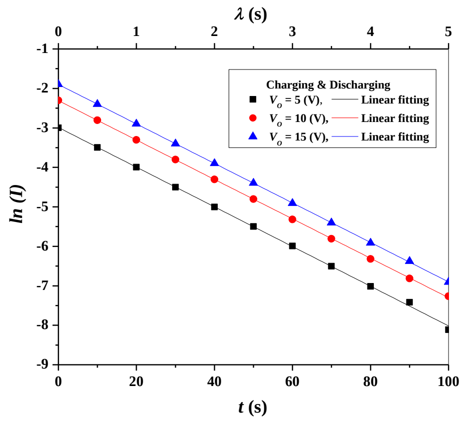


Figure (13): *ln* (*I* (*t*)) graphs during the charging process of the capacitor for three different values of V_O.

Table (2): The intercepts and slopes of the straight lines plotted in figure (13) and their relevant calculations.

V_O (V)	Intercept = ($ln(I_O)$)	I_O (A)	Slope = 1/ λ (s^{-1})	$\lambda = RC$ (s)
5	-2.988 ± 0.026	0.050 ± 0.001	-0.05028 ± 0.00043	19.889 ± 0.009
10	-2.308 ± 0.009	0.010 ± 0.001	-0.04992 ± 0.00014	20.032 ± 0.003
15	-1.898 ± 0.006	0.150 ± 0.001	-0.05003 ± 0.00009	19.988 ± 0.002

Conclusion

A guiding "PHET" simulation and the relevant derived equations of the charging and discharging a capacitor through a DC circuit are presented. The generated results are utilized to graphically show the behaviors of the capacitor's related quantities during both processes of charging and discharging. Moreover, from the simply derived equations, different definitions of the circuit's time constant value are discussed and obtained from the analyses of the results. This work is targeting the students who study physics at the early levels in the faculties of science and engineering. They can understand how the capacitor is charged and stores the electric energy and how this energy is released through a resistive load. Besides the experimental implementation of the experiment at the laboratory, the simulated experiments are helpful when there is no chance to spend extra times at the laboratory or when the number of students is more than the capacity of the laboratory. Also, the accessibility of simulated experiments at any time or any place would be helpful for the student when he has some tasks to do as homework.

Appendix (1)

Figure (A-1) shows an image of a real experiment of the charging of a capacitor as the students can perform in the laboratory.

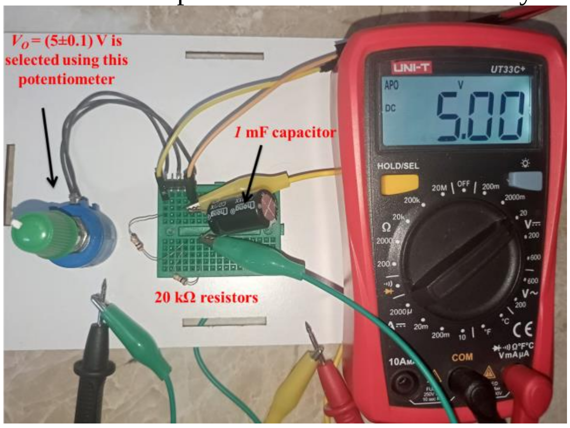
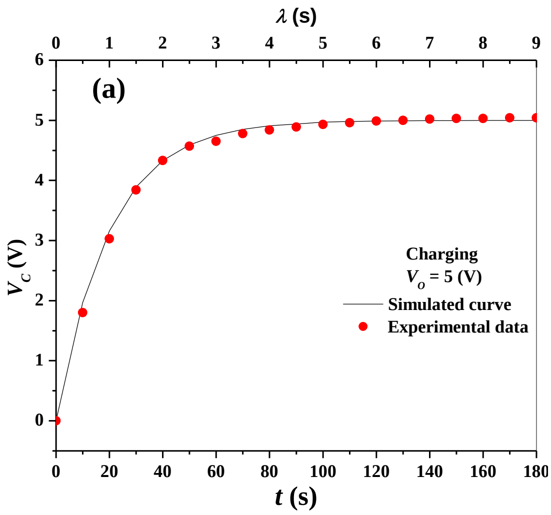


Figure (A-1): An image shows a real experiment of a capacitor's charging when V_C reaches 5 V.

By the aid of the components shown in figure (A-1) and by selecting a resistor of resistance 20 kΩ and a capacitor of capacitance 1 mF (in order to give a time constant 20 (s) as that used in the simulated data), the voltage across the capacitor during the charging and discharging processes is recorded when V_O = (5.0 ± 0.1) V. These experimental values are plotted, the red circles in figure (A-2), and are found matching the corresponding simulated data (for the same parameters) which are represented by the black solid lines in figure (A-2).



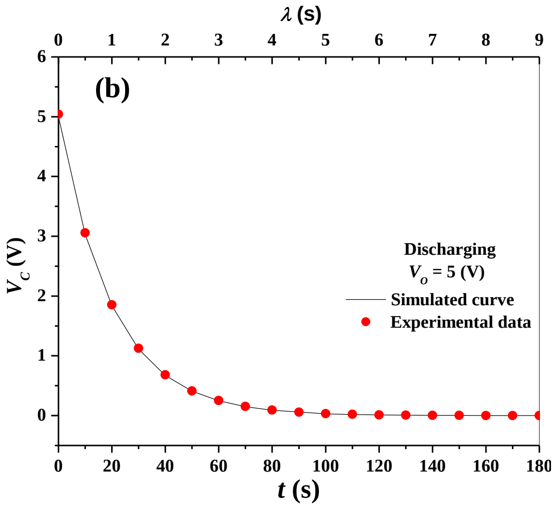


Figure (A-2): The experimentally V_C (*t*) obtained values plotted on the simulated curves, when, V_O = (5.0 ± 0.1) V, in case of (a) charging and (b) discharging a capacitor.

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الملخص العربي

عنوان البحث: شحن وتفريغ مكثف من خلال دائرة تيار مستمر: عرض "PHET" وتحليل البيانات

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تم دراسة عملية شحن وتفريغ مكثف عند توصيله بمصدر جهد مستمر وذلك باستخدام برنامج المحاكاة "PHET" و الذي كان أداة فعالة للتعلم عن بُعد خلال أوقات جائحة "COVID-19". تتكون الدائرة الكهربية المُستخَدمة من بطارية وعنصر مُقاوم ومكثف موصلين على التوالي لدراسة عملية الشحن وكيفية تحوّل جهد البطارية المُطبَّق إلى طاقة كهربية مُختزنة في المكثف. بعد عملية الشحن الكامل للمكثف، تتم إزالة البطارية والسماح للطاقة المختزنة بالتفريغ خلال العنصر المُقاوم. أثناء عمليتي الشحن والتفريغ الكهربي، يتم تسجيل تغير قيم فرق الجهد عبر طرفي المكثف ومن ثَمّ استخدام هذه القيم للحصول على كميات فيزيائية أخرى ذات صلة. تم عرض اشتقاق العلاقات الرياضية (الخاصة بهذه التجربة) بأكملها وبصورة مبسطة ومترابطة وذلك للتيسير على الطلاب الدارسين لهذه التجارب الحصول على المعلومات النظرية المتعلقة بها، حيث وُجِدَ أن هناك بعض القصور في فهم هذه النظريات لدى طلاب المستويات الجامعية الأولى بكليات العلوم والهندسة وذلك لوجود بعض الصعوبات في فهم الاشتقاقات الموجزة للمعادلات الرئيسية في كتب الفيزياء. لذلك، فإن تقييم تجربة المحاكاة والاشتقاقات الرياضية التفصيلية وكذلك تحليل البيانات التي تم الحصول عليها من شأنه أن يرسخ للفهم العميق لأهداف التجربة قيد الدراسة.