IB · DP · Physics

3 hours 14 questions

Structured Questions

11.3 Capacitance

11.3.1 Capacitance / 11.3.2 Dielectric Materials / 11.3.3 Capacitors in Series & Parallel / 11.3.4 The Time Constant / 11.3.5 Energy Stored in a Capacitor / 11.3.6 Capacitor Charge & Discharge / 11.3.7 Discharge Calculations

Easy (5 questions)	/53
Medium (5 questions)	/55
Hard (4 questions)	/46
Total Marks	**/154**

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Easy Questions

1 (a) The capacitance of a capacitor including a dielectric material is given by the equation:

$$C = \varepsilon \frac{A}{d}$$

Determine the following variables and state an appropriate unit for each:

(i) ε

[1]

(ii) A

[1]

(iii) d

[1]

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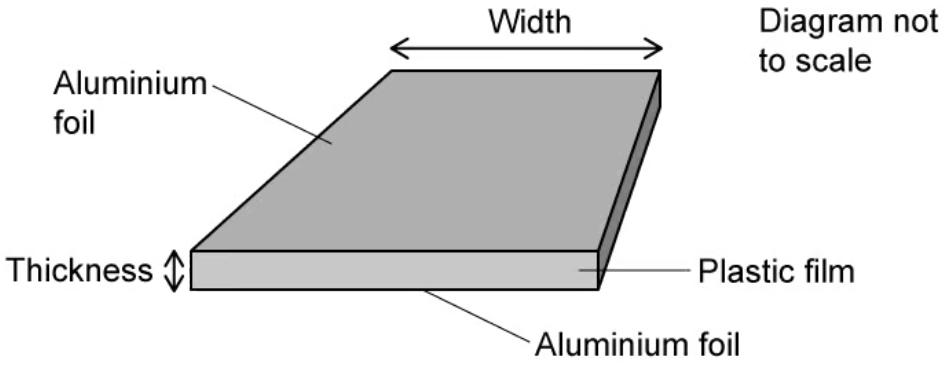
(3 marks)

(b) A student makes a parallel-plate capacitor of capacitance 78 nF from aluminium foil and plastic film by inserting one sheet of plastic film between two sheets of aluminium foil.

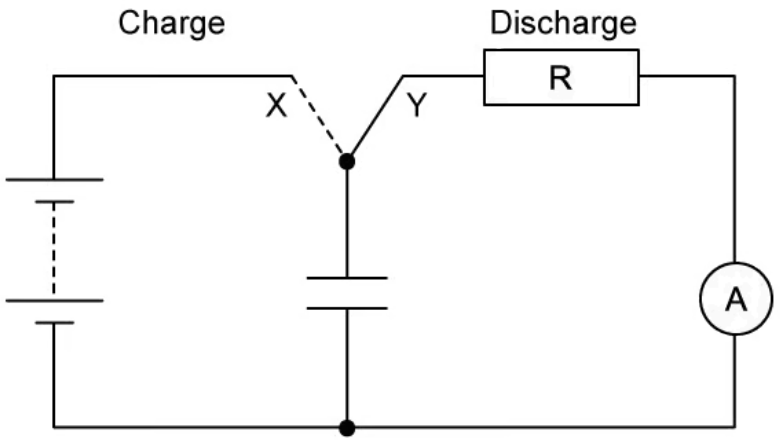


The aluminium foil has an area of 0.28 m^2 and the plastic film has a permittivity of 2.5 × 10^{-11} C^2 N^{-1} m^{-2}.

Calculate the thickness of the plastic film.

(4 marks)

(c) The student uses a switch to charge and discharge the capacitor in the circuit shown. The ammeter is ideal.



The time constant of the capacitor is 0.24 ms.

Show that the resistance of resistor *R* is 3.1 kΩ.

(4 marks)

(d) The emf of the battery is 15 V.

Calculate the initial charge of the capacitor before it is discharged.

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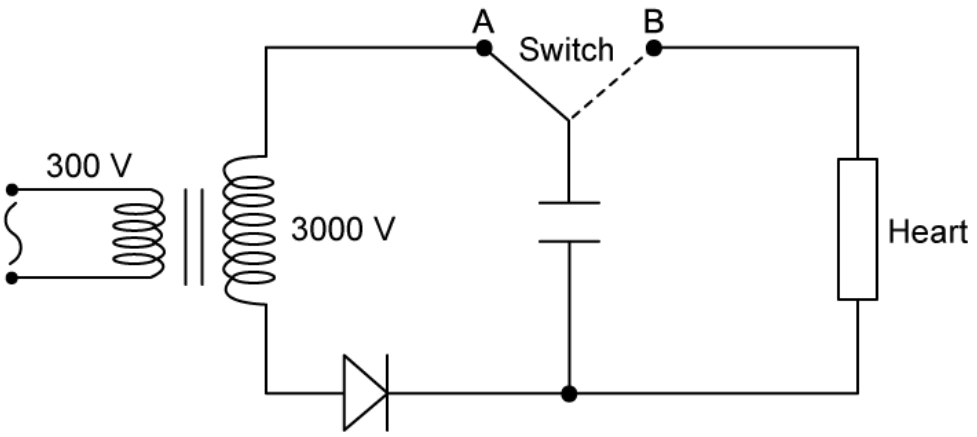
(3 marks)

2 (a) A defibrillator device sends an impulse of electrical energy to maintain a regular heartbeat in a person. The device is powered by an alternating current (ac) supply connected to a step-up transformer that charges a capacitor of capacitance 20 μF. The voltage in the circuit is 3000 V.



Calculate the maximum energy stored in the capacitor.

(3 marks)

(b) Calculate the maximum charge, q stored in the capacitor.

(2 marks)

(c) The current in the circuit passes through the diode from left to right following the direction of the triangle symbol.

Identify, by drawing a +, the positive plate of the capacitor.

(1 mark)

(d) The switch is moved to position B.

State what happens to the energy stored in the capacitor when the switch is moved to position B.

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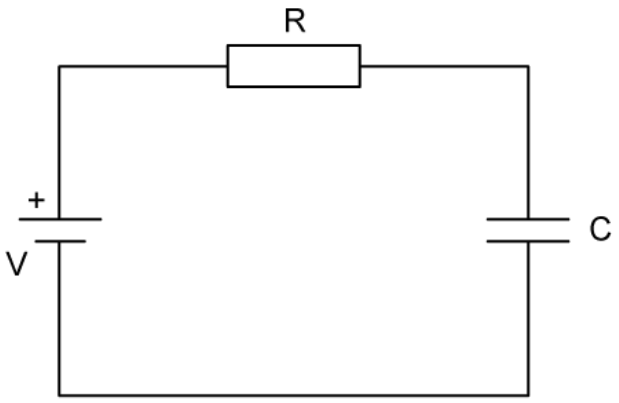
(1 mark)

3 (a) A circuit containing a power supply *V*, a resistor *R* and a capacitor *C* is constructed in a laboratory.



Define the meaning of the time constant for a discharging capacitor.

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(1 mark)

(b) The resistor, *R* in the experiment is fixed at a resistance of 100 Ω and the capacitor, *C* has a capacitance of 25 μF and is discharging.

Calculate the time constant of the circuit.

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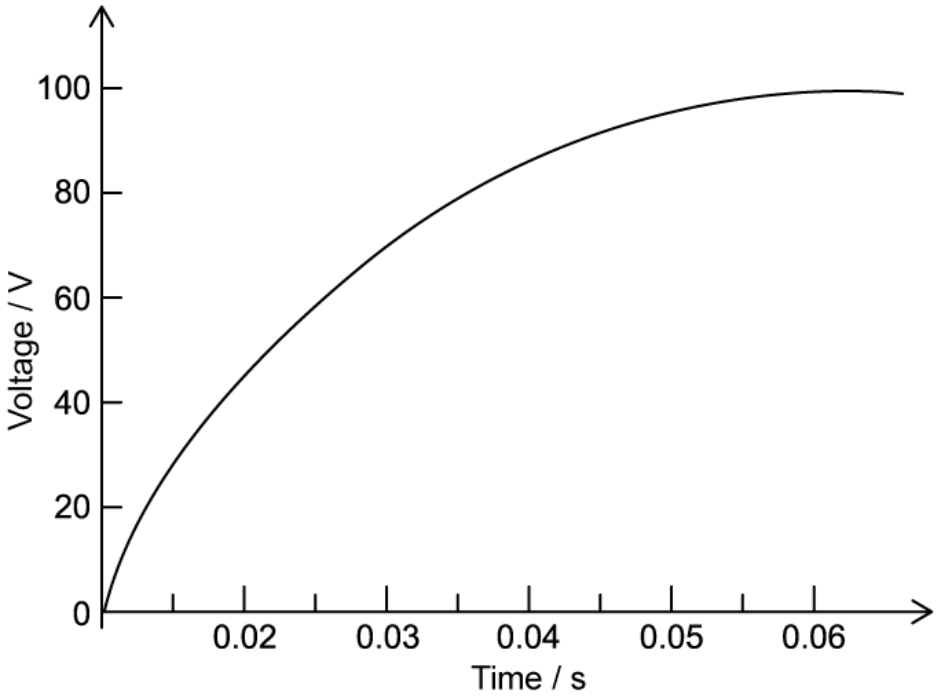
(2 marks)

(c) A different resistor and capacitor are now added to the circuit from (a). The capacitor is charging.



Use the graph to state the value of the time constant for this new circuit.

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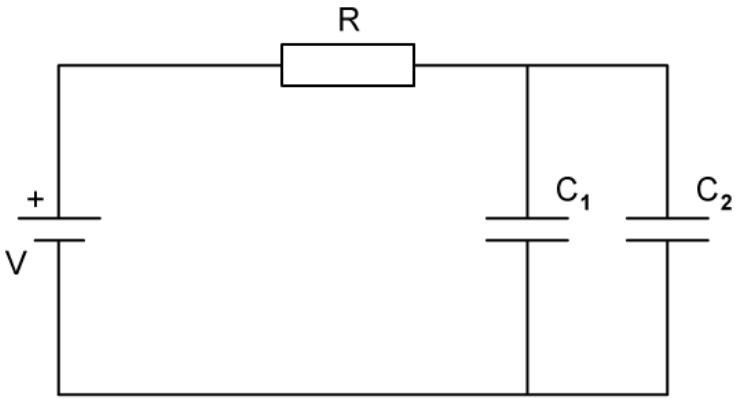
(2 marks)

(d) An additional capacitor C_2 is added in parallel to the circuit.



State the effect on the charge stored in the circuit after adding this additional capacitor.

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(1 mark)

4 (a) Define capacitance.

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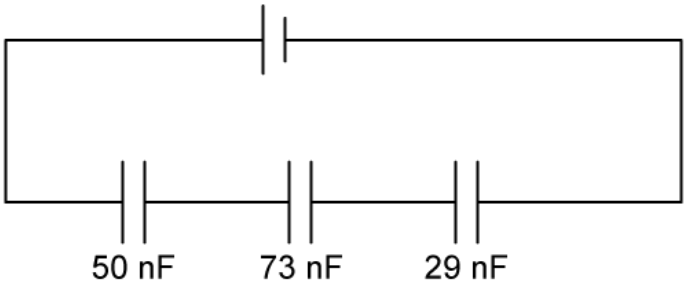
(1 mark)

(b) Three capacitors are connected to a power supply.



Calculate the combined capacitance in this circuit.

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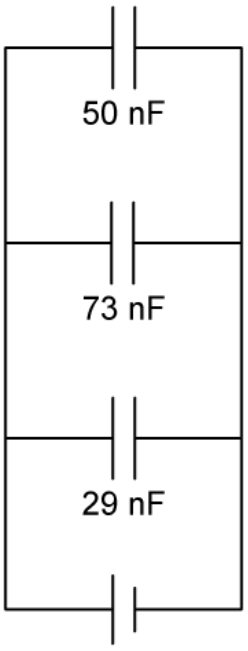
(3 marks)

(c) The capacitors in part (b) are arranged into a parallel combination.



Determine the new total capacitance of the circuit.

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(2 marks)

(d) A parallel plate capacitor has plates of area 0.680 m^2, which are separated by a distance of 5.50 mm in a vacuum. The capacitor is connected to a dc source of potential difference 8.00 kV. :

Calculate

(i) The capacitance of the capacitor.

[2]

(ii) The charge on one of the plates.

[3]

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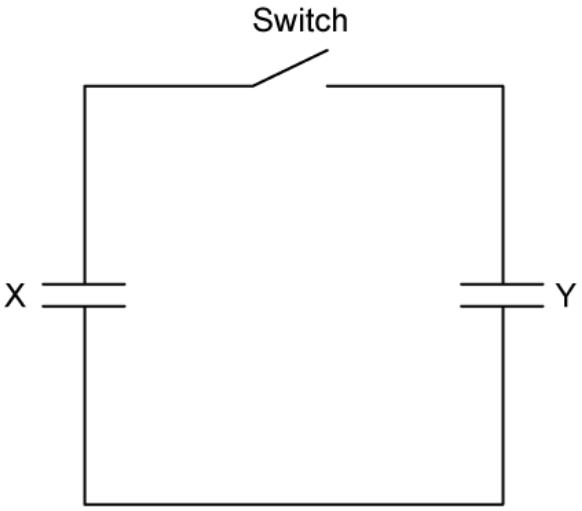
(5 marks)

5 (a) The diagram shows two capacitors, X and Y, connected in a series circuit.



For the time after the switch is closed and when charge has stopped moving, write equations which would determine:

(i) The initial and final values of charge on the capacitors in terms of q.

[1]

(ii) The ratio of the final charges on the two capacitors, $\frac{q_X}{q_Y}$ in terms of q and C.

[3]

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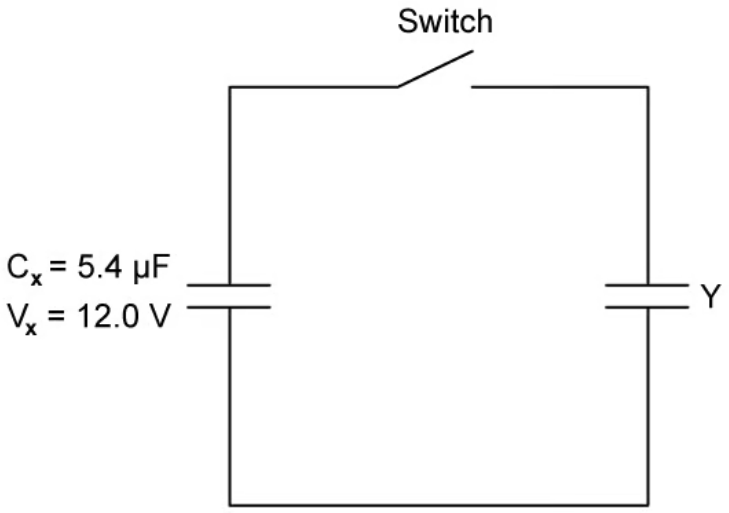
(4 marks)

(b) Capacitor X has capacitance of 5.40 μF and has initially been charged by connecting it to a source of emf 12.0 V.



Using the equations from part (a) or otherwise, calculate the charge

(i) Initially on capacitor X.

[2]

(ii) Finally the total on both capacitors X and Y.

[1]

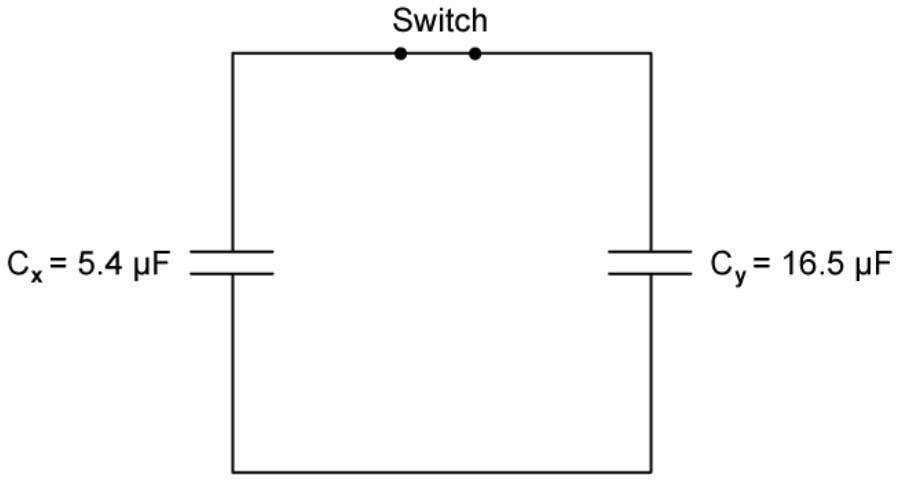
(3 marks)

(c) Capacitor Y has capacitance C_Y and is initially uncharged.

Using the two equations derived in part (a), find an expression in terms of q and C to determine the final values of the charges on each capacitor.

(3 marks)

(d) The value of C_Y = 16.5 μF.

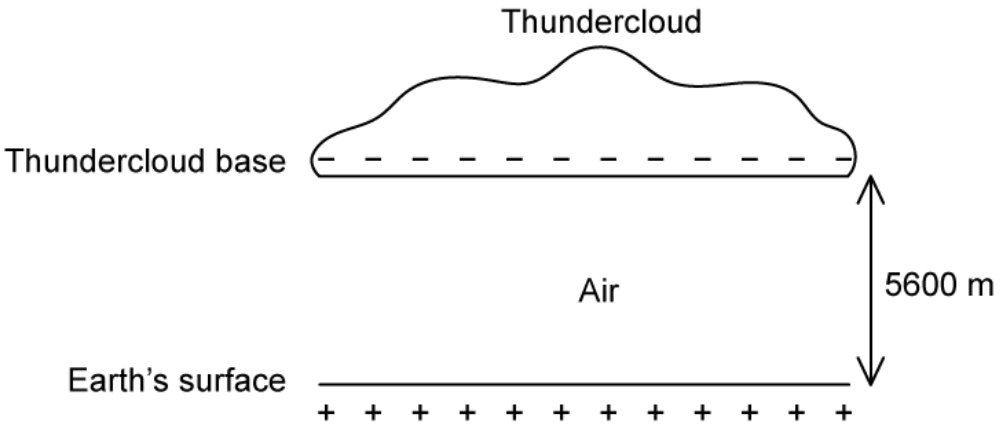


Use this value to calculate the magnitudes of both charges, q_X and q_Y after the switch has closed and charge has stopped moving.

(5 marks)

Medium Questions

1 (a) A negatively charged thundercloud above the Earth's surface may be modelled by a parallel plate capacitor.



The lower plate of the capacitor is the Earth's surface and the upper plate is the base of the thundercloud.

The following data are available.

Area of thunder cloud base = 4.7×10^{12} cm^2

Distance of thundercloud base from Earth's surface = 5600 m

Permittivity of air = 8.8 pF m^{-1}

Lightning takes place when the capacitor discharges through the air between the thundercloud and the Earth's surface. The time constant of the system is 48 ms. A lightning strike lasts for 25 ms.

Show that the capacitance of this arrangement is C = 740 nF.

(2 marks)

(b) The energy stored in the system is 1.2 GJ.

(i) Calculate in V, the potential difference between the thundercloud and the Earth's surface.

[2]

(ii) Calculate in C, the charge on the thundercloud base.

[2]

(4 marks)

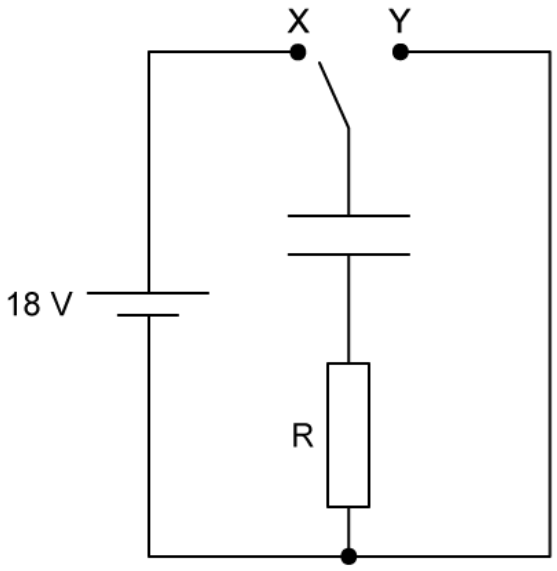
(c) Calculate, in A, the average current during the discharge.

(4 marks)

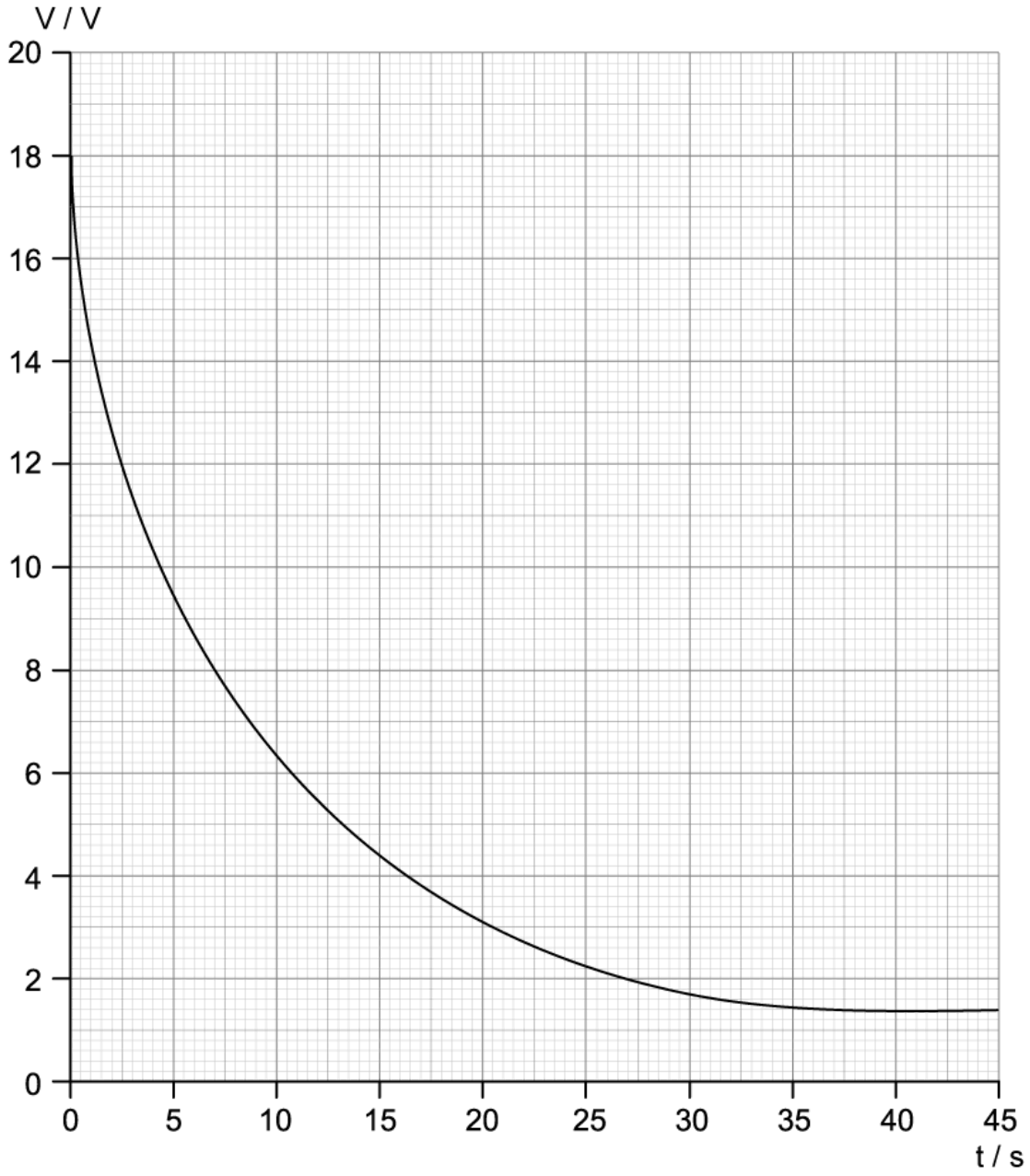
(d) State **two** assumptions that need to be made so that the Earth-thundercloud system may be modelled by a parallel plate capacitor.

(2 marks)

2 (a) An uncharged capacitor in a vacuum is connected to a cell of emf 18 V and negligible internal resistance. A resistor of resistance *R* is also connected.



At *t* = 0 the switch is placed at position Y. The graph shows the variation with time *t* of the voltage *V* across the capacitor. The capacitor has capacitance 2.8 μF in a vacuum.



On the axes, draw a graph to show the variation with time of the voltage across the resistor when the switch is placed at position X.

(2 marks)

(b) Show that the resistance *R* is about 3.0 MΩ.

(3 marks)

(c) Outline the effects of inserting a dielectric between the plates of the fully charged capacitor.

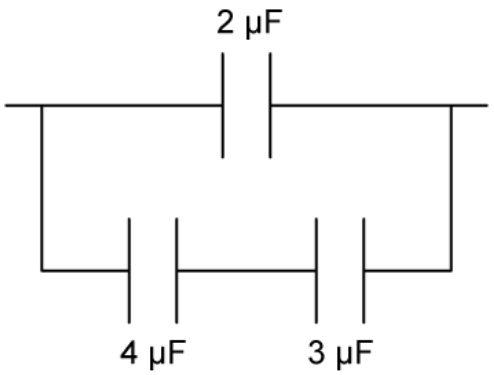
(2 marks)

(d) The permittivity of the dielectric material in (c) is 2.5 times that of a vacuum.

Show that the energy stored in the capacitor is about 1.1 mJ when it is at position X for some time.

(2 marks)

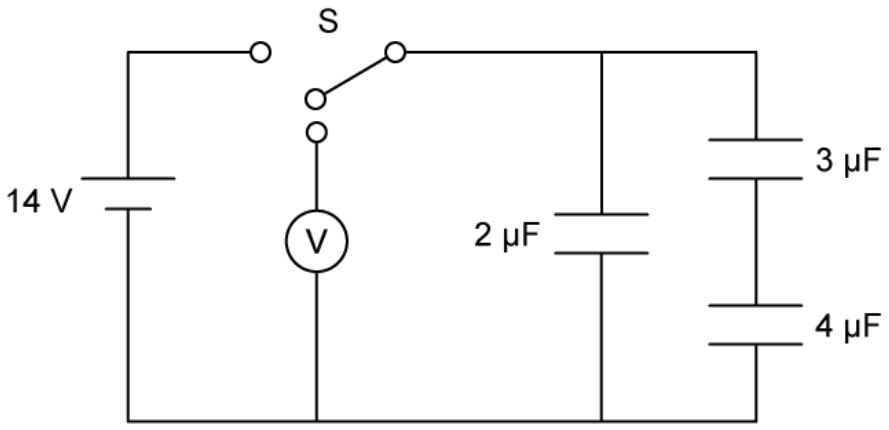
3 (a) Three capacitors are connected below.



Calculate the combined capacitance of the capacitors.

(3 marks)

(b) The capacitors are now connected in a circuit. A two-way switch S can connect the capacitors either to a d.c. supply, of e.m.f. 14 V, or to a voltmeter.



The switch is first connected to the d.c. supply.

Explain why the energy stored in the 2 μF capacitor is greater than the energy stored by the combined 3 μF and 4 μF capacitors.

(4 marks)

(c) The switch S is moved to connect the charged capacitors to the voltmeter. The voltmeter has an internal resistance of 25 MΩ.

State and explain how the capacitors will discharge.

(2 marks)

(d) Calculate the time *t* taken for the voltmeter reading to fall to half of its initial reading.

(3 marks)

4 (a) A capacitor consists of two parallel square pieces of aluminium separated by a vacuum 1.5 mm apart. The capacitance of the capacitor is 2.9 nF

Calculate the length of one side of the plates.

(3 marks)

(b) A sheet of plastic film is placed between the foil which has $\varepsilon = 5\varepsilon_0$.

It begins to conduct when the electric field strength in it exceeds 4.3 MN C^{-1}.

(i) Calculate the maximum charge that can be stored on the capacitor.

[3]

(ii) Explain why the plastic film does not conduct below an electric field strength of 4.3 MN C^{-1}.

[1]

(4 marks)

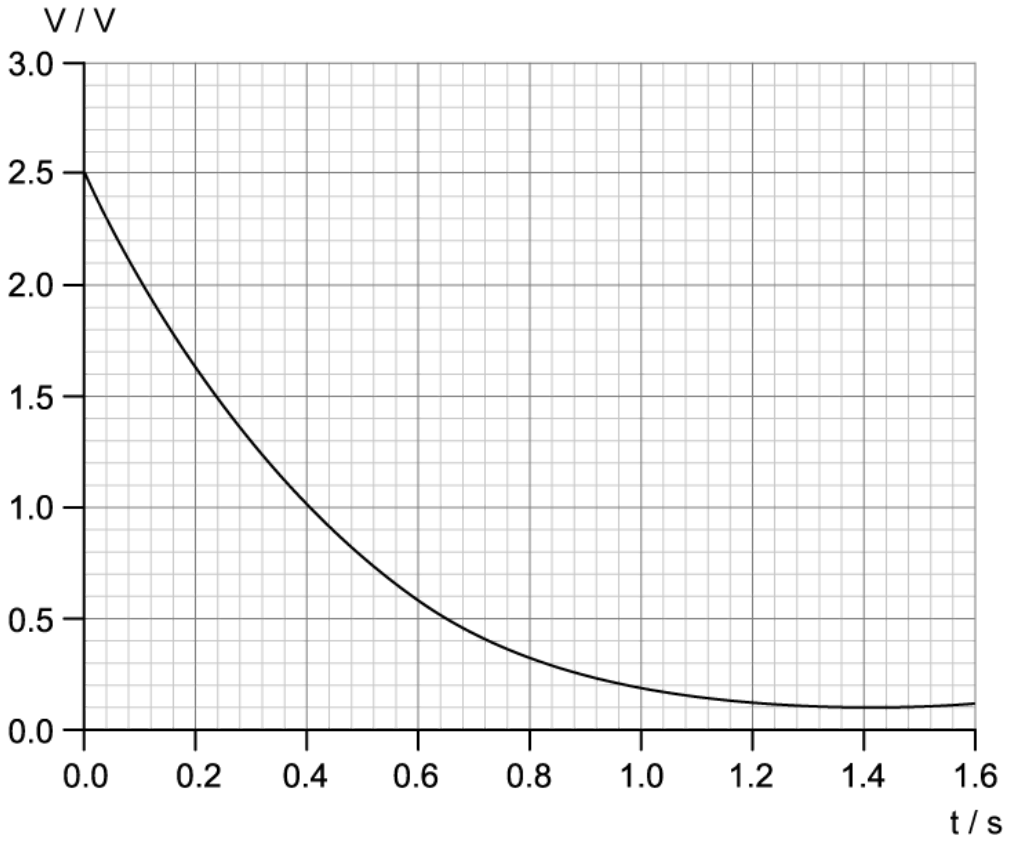
(c) Show that the change in maximum potential difference between the capacitor before and after the plastic film was introduced Is 26 kV.

(3 marks)

(d) Explain how the energy stored in the capacitor changes when the plastic film has been added.

(3 marks)

5 (a) A capacitor of capacitance C_1 is discharged through a resistor of 550 MΩ. The graph shows the variation with time t of the voltage V across the capacitor.



Calculate the value of C_1.

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(3 marks)

(b) The capacitor is changed to one of value 2 C_1 and the resistor to one that is 1100 MΩ.

Sketch on the graph the variation with t of V when the new combination is discharged.

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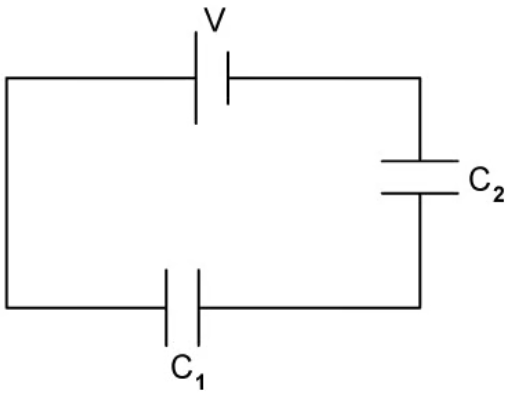
(2 marks)

(c) The capacitor from part (a) is now connected in series with another capacitor of capacitance, C_2. They are both fully charged by a potential difference V. Their combined capacitance is 0.3 nF.



Calculate the value of C_2.

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(2 marks)

(d) Each capacitor holds a charge of 3.6 nC.

Calculate the value of V.

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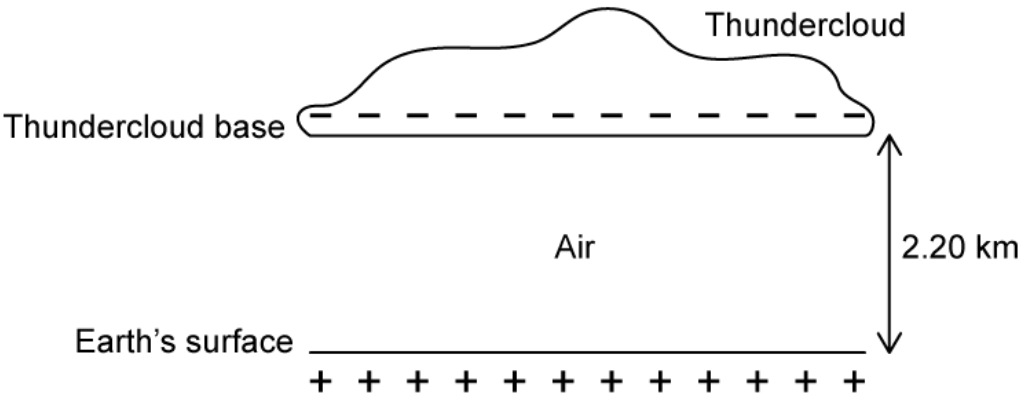
(2 marks)

Hard Questions

1 (a) A thundercloud is 2.20 km above the surface of Earth. The charge on the base of the cloud is −30.0 C. The air between the cloud and the Earth is humid and rainy, making it 4.35 % water by mass.



The relative permittivity for a homogenous mixed medium, $\varepsilon_{r(m)}$, is given by:

$$\varepsilon_{r(m)} = \phi_1 \varepsilon_{r(1)} + \phi_2 \varepsilon_{r(2)}$$

Where $\varepsilon_{r(1)}$ & $\varepsilon_{r(2)}$ represent the relative permittivities of each material in the mixture and Φ_1 & Φ_2 represent the fraction by mass of each material.

The permittivity of water is 7.08×10^{-10} F m^{-1} and the permittivity of air is 8.85×10^{-12} F m^{-1}.

Show that the dielectric constant of the rainy air is about 4.

(4 marks)

(b) The cloud has a roughly rectangular base of length 5.00 km and the potential difference from the base of the cloud to Earth is -8.00×10^8 V.

Calculate the width of the cloud.

(3 marks)

(c) Lightning strikes a tree after strong winds increase the potential difference of the system to -9.0×10^9 V. Air conducts electricity once there is a potential difference of 3.00×10^6 V per metre.

Given that, in a storm, the rainy air has a resistance of 136 $\Omega\ m^{-1}$, determine the time period of the lightning strike.

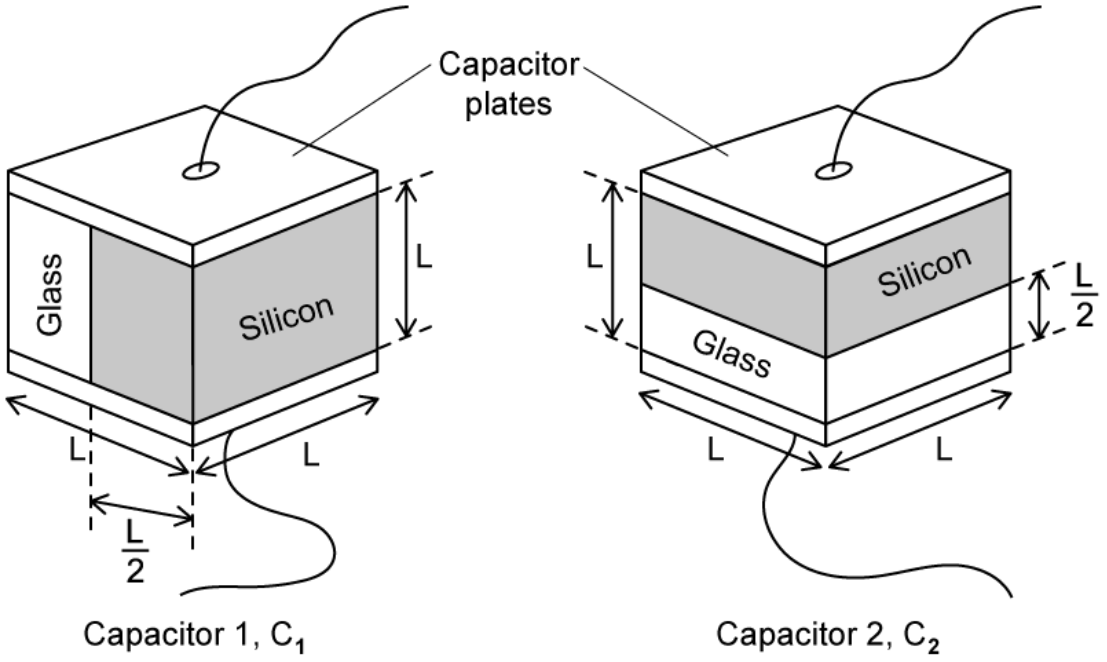
Assume the cloud's area and distance from the ground are unchanged by the wind.

(4 marks)

2 (a) A tattoo removal company uses a pulsed Nd:YAG laser used a capacitor to store energy and produce a short laser pulse. When pulses in the nanosecond range are discharged, tattoo pigments are removed without damaging skin cells.

The research and design team of a company that produces these lasers are experimenting with different dielectrics in the capacitor. One suggestion is to use a cubic dielectric material that is half glass, with permittivity ε_G, and half silicon, with permittivity ε_{Si}, split down the middle.

This mixed medium is used in two orientations during tests.



The capacitor with the dielectric split vertically has a capacitance of C_1 and the capacitor with the dielectric split down the middle has a capacitance of C_2.

Write an expression for capacitance, C_1, in terms of L, ε_G and ε_{Si}.

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(3 marks)

(b) Write an expression for capacitance, C_2, in terms of L, ε_G and ε_{Si}.

(4 marks)

(c) Capacitor 1 and capacitor two are connected in two different circuits. The charge on capacitor 1 is twice that of capacitor 2.

The dielectric constant of the silicon is 4.3 and the relative permittivity of the glass is 6.5

Show that the energy stored in capacitor 2 is 26 % of the energy stored in capacitor 1.

(i) Show that $\frac{E_2}{E_1} = \frac{(\varepsilon_{Si} + \varepsilon_G)^2}{16\varepsilon_G\varepsilon_{Si}}$, where E_n is the energy stored in capacitor n and ε_z is the permittivity of material z.

[3]

(ii) Calculate E_2 as a percentage of E_1.

[2]

(6 marks)

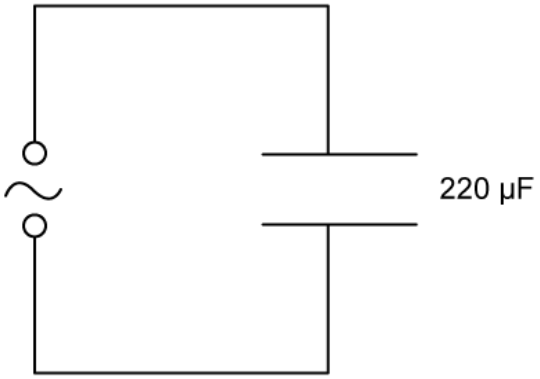
3 (a) A capacitor with capacitance 220 μF is attached to an ac voltage source which provides a voltage which varies according to the following equation:

$$V = V_0 \sin(\omega t)$$

The rate of change of the voltage is given by:

$$\frac{\Delta V}{\Delta t} = \omega V_0 \cos(\omega t)$$

This circuit is called 'purely capacitive', meaning that resistance can be assumed to be zero.

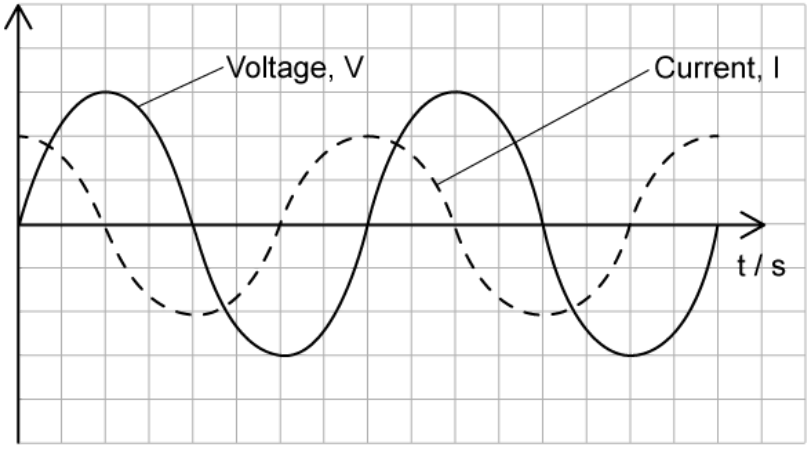


The power supply is adjusted such that the initial voltage is 6.0 V and the alternating voltage frequency is 4000 rad s^{-1}.

Calculate the magnitude of the current flowing in the circuit at time t = 3.14 s.

(4 marks)

(b) The variation of voltage *V* and current *I* in the circuit is shown.



Discuss the phase difference between the variation of *V* and *I* in the circuit.

(3 marks)

(c) 'Capacitive reactance' *X* is the opposition to current flow in a purely capacitive circuit as described in part (a). Capacitive reactance is comparative to resistance, in that it is measured by the same units Ω.

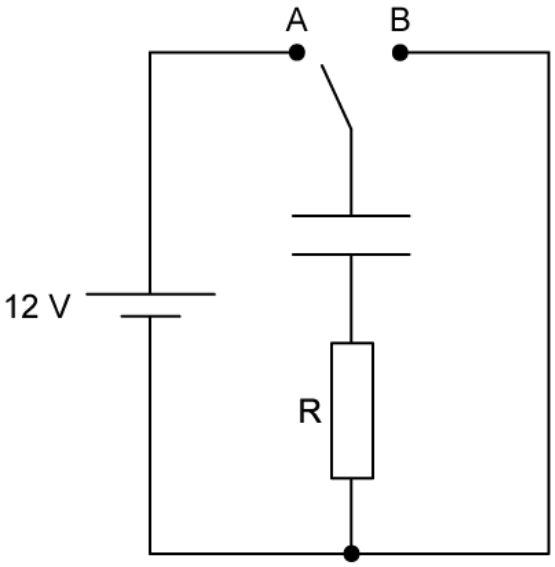
By considering the ratio of the maximum voltage and current in the circuit, show that the capacitive reactance *X* is given by

$$X = \frac{1}{\omega C}$$

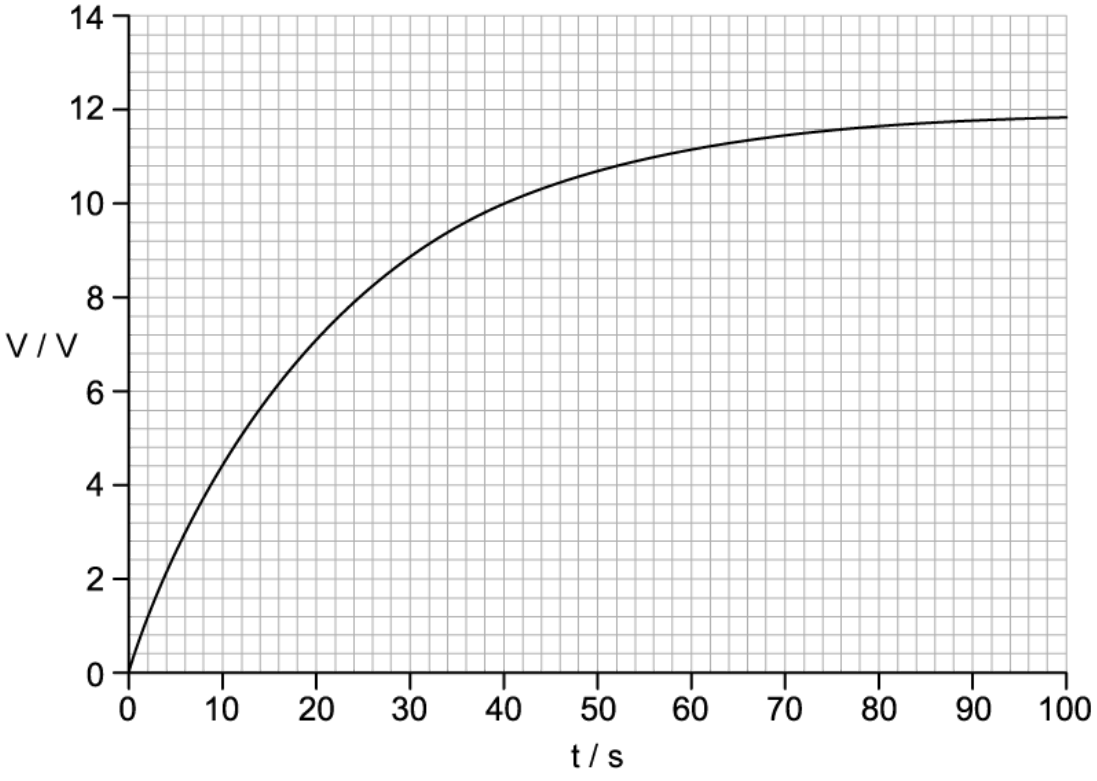
and verify that *X* has the same units as resistance.

(4 marks)

4 (a) A vacuum capacitor is connected, along with a resistor, to a cell with an emf of 12 V in the configuration below. In a vacuum, the capacitor has a capacitance of 4.5 μF.



Initially, the vacuum capacitor is uncharged. At a time of t = 0 s, the switch is placed at position A. The voltage across the capacitor is recorded over time and plotted in the graph below.



Sketch a second line on the axes, showing the variation in the voltage across the resistor over time.

(2 marks)

(b) Using the graph, calculate the resistance, *R*, of the resistor.

(3 marks)

(c) The vacuum chamber is now filled with acetone, which has a dielectric constant of 19.5.

Calculate the new charge stored in the capacitor when the voltage across the capacitor is half its maximum value.

(3 marks)

(d) Once the capacitor is fully charged, the switch in the diagram in part (a) changes to position B.

(i) Describe the energy changes in the capacitor.

[1]

(ii) Explain why these energy changes occur.

[2]

(3 marks)