Experiment # 2

Insulators: Capacitance

Principles

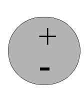
Insulators & Bound Electrons

The binding energy of valence electrons of atoms of elements in our Periodic Table, varies considerably from element to element. For atoms of some elements it is found to be large or very large. Electrons of atoms of such elements are tightly bound to their nuclei and cannot be pulled out easily. These atoms, therefore, cannot be ionized using normal ionizing techniques; a sufficiently large force, however, will ionize any atom. Materials and substances made from such elements are called *insulators* (or *nonconductors*). In Insulator materials, therefore, all electrons remain firmly fixed to their nuclei and forever stay in their respective orbits. Examples of insulators are rubber, plastics, wood, air, distilled water etc. In fact there are more insulator materials and substances in the Universe than conducting ones.

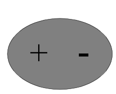
Insulators: Inside Story - Electrically Speaking.

The charge distribution of atoms and molecules of insulator materials is, in general, not uniform. Some parts of the molecules are found to be more positive (or negative) than others; even though, on an overall basis, the net charge remains zero. Molecules with symmetric or isotropic charge distribution are represented by spheres while those with anisotropic or asymmetric charge distributions are represented by ellipsoids, as shown in Fig (1a) and (1b).

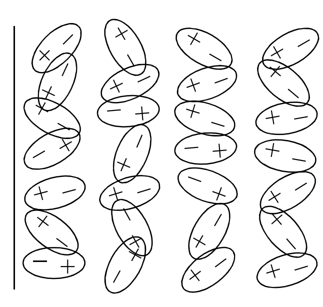
The departure of charge distribution from being symmetrical (in an atom or molecule) is called *polarization*. The greater the polarization, the greater is the asymmetry of charge distribution, and vice versa. An atom or a molecule with asymmetric (anisotropic) charge distribution is called a *polar* molecule. Molecules of most insulator materials are polar. These polar molecules are randomly oriented inside the body of the insulator material. This is shown in Fig (1c).



(1a) Isotropic Charge Distribution



(1b) Anisotropic Charge Distribution



(1c) Fields are absent

Fig (1) Isotropic and Anisotropic Charge Distribution for Atoms or Molecules

Placing the Insulator Material in an Electric Field

To study the interaction of electricity with insulator materials, we need to submerge them in electric fields. For the study to be meaningful and quantitative, however, the field must be *uniform.* Uniform electric fields can *only* be produced in between a pair of parallel metallic plates, connected to a voltage source. It will be natural, therefore, to have the insulator material in the form of a rectangular block so that it would fit snugly in between the assigned pair of plates.

Consider a rectangular block of an insulator material of cross-sectional area A and width d. We place the block in between a pair of parallel metallic plates, also of area A. When set in position, the two plates will be a distance d apart, which of course, is the width of the insulator block.

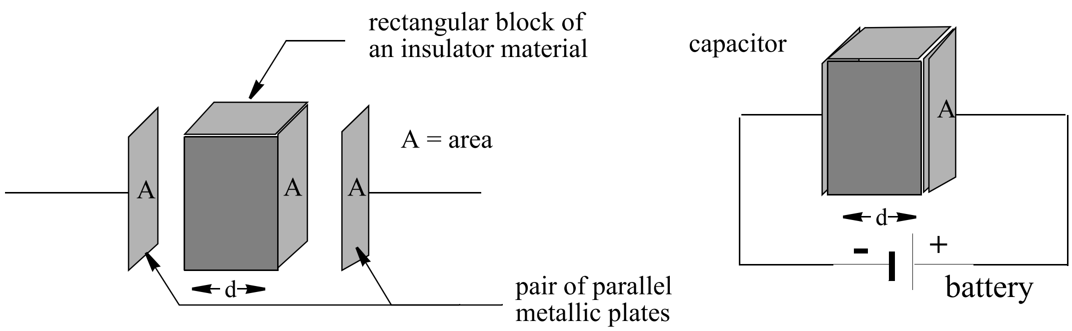


Fig (2) Placing an Insulator in an Electric Field

When the metallic plates are connected to a battery of voltage V_S, the battery tries to send electrons through the insulator material. Such efforts are frustrated because the block of the insulator material could not and would not let electrons pass through its territory. As electrons cannot go into the insulator material, they just keep amassing on the plates. The charges of the amassed electrons quickly build an electric field. This field grows in intensity and soon becomes strong enough to successfully exert a repulsive force on freshly arriving electrons, thereby preventing them from getting on-board the plates. We say that a state of *equilibrium* is established or a *steady state* is reached. In the steady state, a fixed number of electrons stay on one plate. An equal number of positive ions is seated on the other plate. Resident charges, $\pm Q$ are of well-defined magnitudes. The uniform (net) electric field produced by resident charges obeys the equation;

$$V = Ed \qquad \text{..........(1)}$$

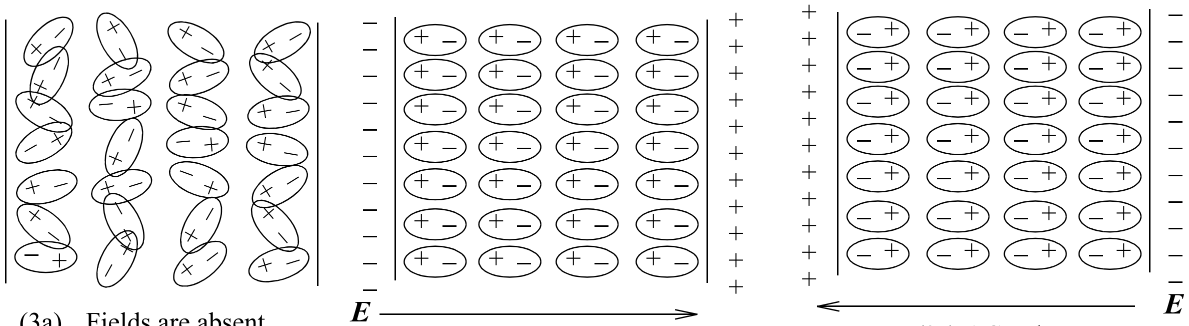
The Interaction: (A) - How Does Electricity Affect the Insulator Material?

Electricity (the Electric Field) Rotates the Polar Molecules

The uniform electric field exerts a torque on the polar molecules which causes them to rotate (or to try to rotate) about an axis through their center of mass. As a result, the part of the molecule with excess positive charge faces the negatively charged plate and vice versa. This is shown in Fig (3) and explained thereafter.

And that's the end of the interaction.

Fig (3a) shows unaligned molecules of an insulator. Fig (3b) shows the alignment produced by the electric field of DC electricity. Again Figs (3b) and (3c) show the alignment produced by the electric field of AC electricity. In case of DC electricity, the field remains constant at



(3a) Fields are absent

(3b) DC voltage
OR AC voltage (one-half of the cycle)

(3c) AC voltage
(the other half of the cycle)

Fig (3) Rotation of Atoms and Molecules of an Insulator

all times. In case of AC electricity, the field is continuously changing but the change affects the entire insulator block uniformly at any instant of time. The diagrams show fully aligned molecules in the presence of fields but this may not always be the case.

Magnitude of Rotation of Polar Molecules

The degree of alignment of the polar molecules of the insulator-block with the applied electric field, is a direct consequence of the degree of rotation of the molecules. The degree of rotation of the molecules, in turn, is a direct consequence of the strength of the net electric field E, established inside the insulator-block. The strength of the net electric field E, in its turn, is a direct consequence of the resident charges $\pm Q$, supplied by the battery. A battery is the sole provider of electrical charges.

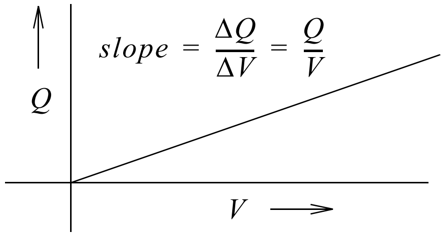
The greater the magnitude of resident charges, the greater will be the strength of the net field and greater will (eventually) be the alignment of the molecules with the field. (and *vice versa*). We expect the capability of the battery to provide resident charges, to depend on the driving force (the emf) of the battery, expressed in terms of its voltage V_S (source voltage). The net outcome of this chain of *direct consequences* is that if V_S is large, the alignment of molecules will be large and vice versa. We can, therefore, use the *quantity of resident charges* as a measure of the *degree of alignment* of the polar molecules.

Having eliminated (i) the degree of alignment, and (ii) the net electric field, we are left with (i) resident charges $\pm Q$, (or simply Q) and (ii) supply voltage V_S (or simply V). Using a source of variable voltage (denoted by V) and a charge-monitoring device (a charge-meter), we perform an experiment. We apply different voltages V to the insulator-block and monitor the corresponding resident charges Q. Plotting voltages V on the x-axis and the charges Q, on the y-axis, we find that our line of arguments was indeed correct. The graph yields a straight line, telling us that the quantity of resident charges Q, is directly proportional to the voltage V, supplied by the battery.

The slope of the straight line will be $\Delta Q/\Delta V$ but as the line passes through the origin, we are permitted to write the slope simply as Q/V. (Obviously when V is zero, Q must be zero too.)

We define Q/V as C and write:

$$C = \frac{Q}{V} \qquad \text{..........(2)}$$



$$\text{let } \frac{Q}{V} = C$$

$$\text{then } \quad Q = CV$$

Fig (4) Dependence of Q on Applied Voltage V

We interpret C as *capacitance*, the ability of the driving force of electricity (in volts) to place charges on the plates (to their full capacity). The unit of C is easily seen to be:

$$\frac{C}{J/C} = \frac{C^2}{J} = F$$

The unit has been given the name *farad* for which we write F. A *farad* is a rather large unit and we often use smaller units such *microfarad* μF, *nanofarad* nF, or *picofarad* pF. These are respectively: $\mu F = 1\times10^{-6}\text{F}$, , $nF = 1\times10^{-9}\text{ F}$ or $pF = 1\times10^{-12}\text{ F}$.

Rearranging, Eqn (1) we get an equation for the amount of charge Q, supported by the applied voltage V, to reside on the metallic plates of given size.

$$Q = CV \qquad \text{..........(3)}$$

Eqn (2) is an equation of basic importance, as will be found shortly. We conclude:

The charge deposited on the plates, is proportional to the driving force (emf in volts) of electricity. The constant of proportionality is defined as Capacitance.

The Interaction: (B) - How Does Insulator Material Affect Electricity (the Field)?

Insulator Material Determines the Magnitude of Alignment

If electricity (the field) affects insulator material, then it is imperative that the insulator material will also affect the electric field. It is indeed so. We find that for a given source of electricity, it is the insulator material that determines the extent by which the polar molecules would get aligned with the net electric field E. As degree of alignment is measured in terms of the resident charges Q, we conclude that it must be the insulator material that determines the magnitude of charge Q that would reside on the plates. This we found by doing an intuitive experiment. We made a number of identical rectangular blocks of different insulator materials and using the same battery, we measured the magnitude of resident charges in each case. We found them all to be *different* from one another. So, it is true: each insulator material accepts a certain quantity of resident charges, *totally* specific of its own nature.

The ability of insulator materials and substances, to control the magnitude of resident charges, must come from some inherent electrical property that they posses. The *only* inherent electrical property that all materials and substances posses, is *permittivity.* We write ε for it and its unit is $C^2/(Nm^2)$. So, we have no choice. *Permittivity* is the controlling factor. Going back to the above-mentioned experiment, we next interpret the results in terms of the permittivities of the materials used. Interestingly enough, we find that insulator materials with larger permittivity values (such as glass) had larger number of resident charges, compared to the ones with lesser permittivity values (such as wood). It is, therefore, evident that the greater the permittivity of an insulator material, the greater will be the quantity of resident charges on its plates. (and vice versa). The relationship turned out to be linear, we dare to write:

$$Q \propto \varepsilon \qquad ....(4)$$

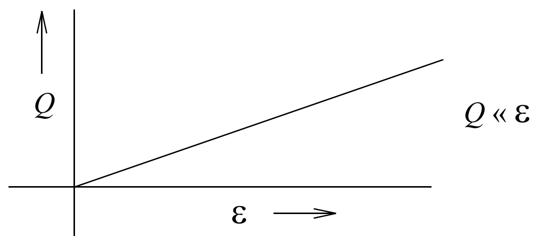


Fig (4) Dependence of Q on permittivity ε

Permittivity is one of the three fundamental properties of matter, in our Universe. The other two are (i) the magnetic permeability μ, and (ii) the Gravitational Constant G. Free space (or vacuum) has permittivity (called ε_o) and permeability, (called μ_o). The numerical value of ε_o is $8.854 \times 10^{-12}\ C^2/(Nm^2)$ and that of μ_o is $4\pi \times 1 \times 10^{-7}\ Tm/A$. It is generally believed that if there were to be another universe, then the numerical values of these three constants for them, will be different from those of ours.

Permittivity ε of insulator materials is said to be of the *static* type. It is *static* simply because the charges are not in motion and are in a state of *static* equilibrium. The magnitude of ε of an insulator material, is always greater than that of free space, ε_o. The ratio of ε to ε_o is defined as the *dielectric constant* of that insulator material and is written as K. Thus $K = \varepsilon/\varepsilon_o$. K is a dimensionless number and is always greater than one. For water molecules $K = 80$; which is a pretty high value for dielectric constants. In fact it is this property of water that has led to the development of microwave ovens (a very useful household appliance).

To replace the sign of proportionality in Eqn (3) by the sign of equality, we introduce a constant:

$$Q = (constant)(\varepsilon) \qquad ....(5)$$

The unit of Q (the left hand side) is just *coulomb* (C) and that of ε is $C^2/(Nm^2)$. To get (C), on the right hand side as well, the *constant* in Eqn (4) must have the unit Nm^2/C. Now Nm^2/C can be considered to be $(N/C)(m^2)$, which would conveniently make EA, both quite the components of our uniform electric field system. If you are worried as to why we just *conveniently* made Nm^2/C as EA, remember that Nm^2/C had to be something belonging to our system under study. It could not, for example, be (torque x displacement per unit charge) or (rotational work per unit charge) or something, something. So we write:

$$Q = (EA)(\varepsilon) = \varepsilon EA \qquad ....(6)$$

We conclude:

The charge deposited on the plates, depends on the nature of the insulator material (in terms of its permittivity) and will vary from one insulator material to another.

Capacitance and Permittivity

When electricity interacted with insulator materials, we got *capacitance* and when insulator materials interacted with electricity, we got *permittivity*. How are the two related?

The end product in each case is alignment of polar molecules, expressed in terms of the charge Q that resides on the pair of parallel metallic plates. Consider Eqn (2), involving capacitance and Eqn (5), involving permittivity. The left hand side in each case, is charge Q. Equating the two right hand sides, we get:

$$CV = \varepsilon EA$$

Writing $V = Ed$ (which is valid for all parallel plate arrangements), we get:

$$CEd = \varepsilon EA$$

Cancelling out E from the two sides and rearranging, we get:

$$C = \frac{\varepsilon A}{d} \qquad \text{..........(7)}$$

Eqn (6) spells out the relationship between *capacitance* and *permittivity*. *Capacitance* depends on the geometrical shapes and sizes of insulator materials. So it must be the property of objects (or devices) that we make from insulating materials. *Permittivity,* on the other hand*,* is independent of geometry, and as such, is the property of insulating *materials and substances* themselves, and not of objects made thereof.

Eqn (6) allows us to calculate the capacitance of an object, made from a given insulator material, by knowing its geometrical shape and size. We wouldn't need a variable voltage source and a charge-meter, any more.

A rectangular block of an insulator material will have three different values of C but only one of ε. The three values of C correspond to the three pairs of faces that the insulator-block has. These are (i) length x width, (ii) width x thickness, and (iii) thickness x length.

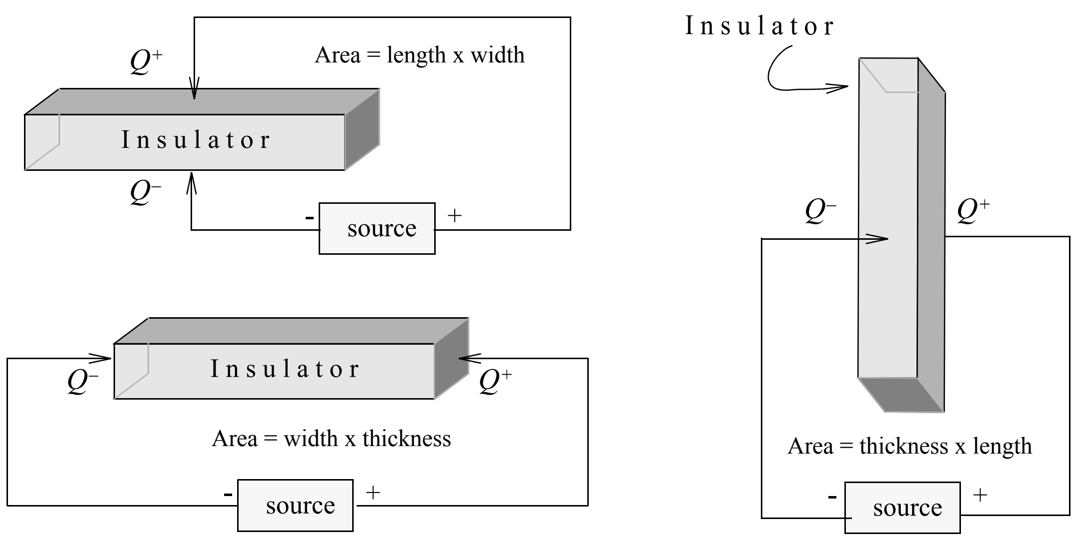


Fig (5) Dependence of Capacitance on the Geometrical Shape & Size of the Insulator Block

Capacitance & Energy!

Capacitance was discovered as the *slope* of a graph. Our curiosity demands that we also explore the other property of graphs: the *area* under the straight line. If it makes sense (from the physics point of view), we shall exploit it for gainful purposes. If not..., well, there is no harm in asking.

It turns out that the area of the triangular space is $(1/2)QV$. The unit is easily seen to be just *joules* or energy. We find the result of investigation to be immensely useful. The insulator material *captured* some energy, which it will hold without dissipation or loss. We write U_C for this energy.

$$U_C = (1/2)QV \qquad ....(8)$$

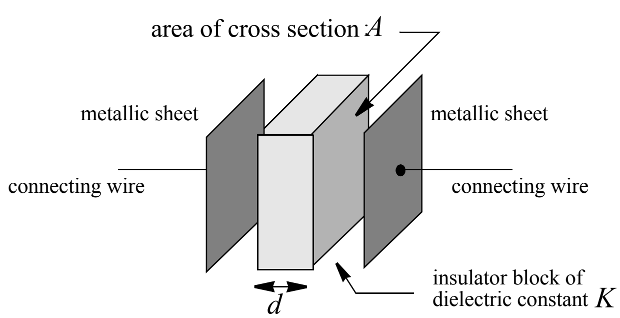
Using the equation $Q = CV$, and $V = Ed$ we get some more equations for determining the magnitude of this energy: The string of expressions is given below:

$$U_C = \left(\frac{1}{2}\right)QV = \left(\frac{1}{2}\right)CV^2 = \frac{Q^2}{2C} = \frac{\varepsilon E^2}{2}(Ad) \qquad ....(9)$$

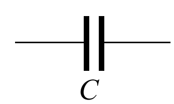
The energy stored, comes from the work done by the electric field on polar molecules in rotating them. As the work is done by an external agency, the energy contents of the molecules increase. It is interesting to note that once energy is delivered, it will stay there, whether the battery remains connected to the parallel plates or removed. In the event the battery, is removed, the charges $\pm Q$ get trapped. They have nowhere to go. So, they will stay on the plates indefinitely.

Capacitor: A Device

The above described interaction of insulator materials with electricity (the field), leads us to develop a device, mainly for the purposes of storing electrical energy. The device is called a *capacitor*. A *capacitor* utilizes the property *capacitance* of insulator materials. It is essentially an insulator material in the form of a rectangular block, to which a pair of parallel metallic plates are attached. The plates each have a cross-sectional area A and are separated by a length d, the width of the insulator block. The electrical symbol of the device *capacitor is* shown in Fig (6). As a device, capacitors are used in practically every electrical instrument/gadget, ranging from fans to televisions, to stereo systems to ipods (and *pads*), computers and the like.



(a) capacitor: anatomy



(b) capacitor, symbol

Fig (6) A Capacitor

We shall, next, place a capacitor in a circuit fed by (i) a DC source of electricity, and (ii) an AC source of electricity, and study its performance, in each case.

Capacitors & DC Electricity: The Capacitor Equation

Fig (7) shows a capacitor connected to a source of DC electricity. Potential difference (or voltage) is applied to the capacitor using connecting wires. The arrow across the battery shows that the voltage is variable. A voltmeter and an ammeter have been added for monitoring the voltages and currents in the circuit. In Fig (7), A and V are respectively an ammeter and a voltmeter.

As insulators do not conduct electricity, charges get deposited on the two metallic plates and Eqn (2) follows, which we now write as:

$$Q_C = C\ V_C \qquad ....(10)$$

This equation is the capacitor equation when it is fed by DC electricity. Even though the equation does not have a specific name (such as Ohm's law, for resistors), it is of paramount importance and is treated as the *master* equation for capacitors in DC circuits.

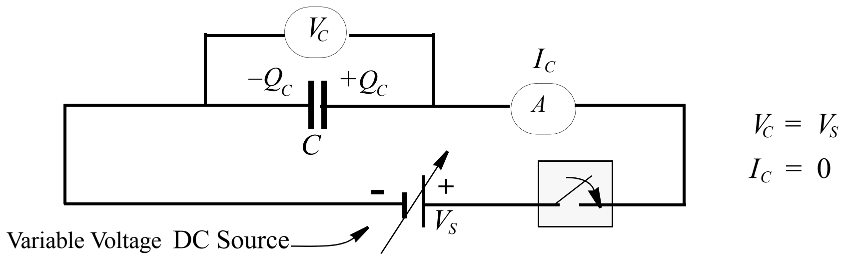


Fig (7) Capacitor in a DC Circuits

Capacitors & AC Electricity: The Pseudo Current

Fig (8) shows a capacitor connected to a source of AC electricity. The circuit is essentially the same as that of Fig (7), but here we have replaced the DC source by an AC source of frequency f Hz. The meters have also been switched to read AC voltage (rms), and AC current (rms).

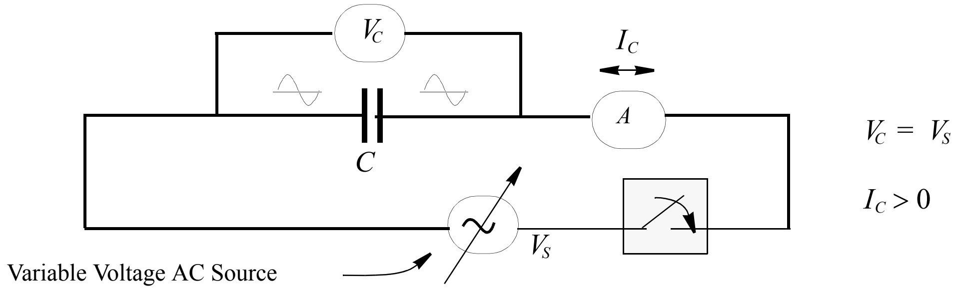


Fig (8) Capacitor in an AC Circuit

Things are radically different now. The source voltage is not constant here, and varies in a sinusoidal manner. The charge deposited on a metallic plate, therefore, is not constant either and changes sinusoidally. On a particular plate, the charges of one polarity grow from zero to maximum and then decrease down to zero. At this point the source switches the direction of flow of electricity and charges of opposite polarity start flowing; growing to maximum and then decaying down to zero. The cycle is repeated with the frequency f of the AC source. The net outcome of this ever-continuing process is that there is always some current in the circuit; flowing in one direction or the other, increasing in magnitude or decreasing.

The ammeter, placed in the circuit, will be able to show this variable flow of charges, in the form of an rms current. This leads one to think that a current is flowing through the insulator material inside the capacitor and that perhaps insulators conduct AC electricity. This is not true! It must be emphasized that all this activity is taking place in the connecting wires only and that no current ever passes *through* the body of the insulator. This apparent conduction is called *pseudo* conduction. The current due to *pseudo* conduction is an alternating current and is shown by AC ammeters only.

It is interesting to point out that, on the face of it, there is no difference in the true current and the pseudo current. If all parts of the circuit were masked and one could only read the current in the ammeter, there would be no way of telling whether the current is a true current or a pseudo current.

To find a mathematical representation for the above behavior, we consider the variation of charge Q_C (residing on the plates), as a result of the time-varying voltage V_C of the AC supply. Recall:

$$Q_C = C\ V_C$$

and operate upon it by the operator $\left(\frac{\Delta}{\Delta t}\right)$. We get:

$$\left(\frac{\Delta}{\Delta t}\right)Q_C = \left(\frac{\Delta}{\Delta t}\right)(C\ V_C)$$

As C is constant, the operator will only operate on V_C. We get:

$$\frac{\Delta Q_C}{\Delta t} = C\ \frac{\Delta\ V_C}{\Delta t}$$

The term on the left hand side: $(\Delta Q_C)/(\Delta t)$ is, by definition, current. This is the pseudo-current I_C, displayed by the ammeter. We get:

$$I_C = C\ \frac{\Delta\ V_C}{\Delta t} \qquad \text{..........(11)}$$

This equation is the capacitor equation when fed by AC electricity.

Reactance

The above derived equation for capacitors in an AC circuit is not exactly a *user friendly* equation. To make it *palatable*, we consider the rotation of the generator coil in an AC generator. The rotation of the generator coil may be represented either in terms of emf ε_S generated in the coil or current I_S that is supplied by it and is applied to some device. Presently we shall consider it to be ε_S. The propagation of rotation results in a sine wave for ε_S. For each cycle of the sine wave, the generator coil will rotate through one circumference of the circle of radius ε_S. The time period of the sine wave is T sec.

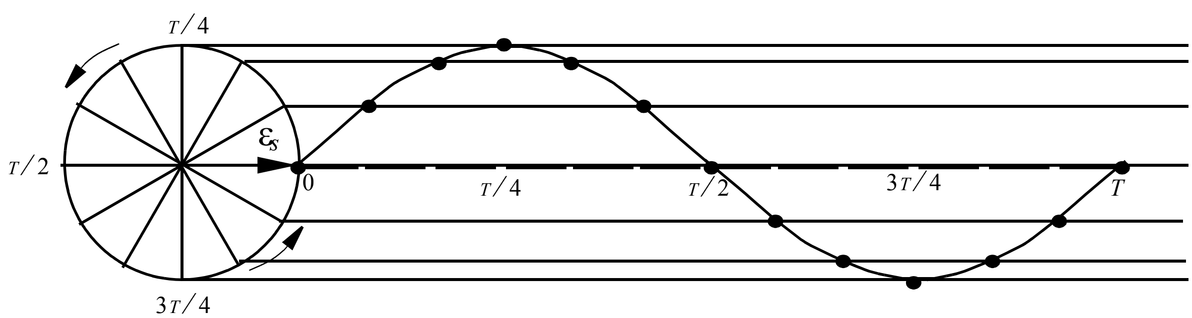


Fig (9) Propagation of Rotation of the Generator Coil in terms of ε_S

Let Δt, in Eqn (10), be one time period T of the sine wave, then $\Delta\varepsilon_S$ will be $2\pi\varepsilon_S$, the circumferential distance traversed by ε_S. we get, from Eqn. (10):

$$I_C = \frac{(C)(2\pi\varepsilon_S)}{T}$$

As $1/T = f$, we get:

$$I_C = (C)(2\pi\varepsilon_S)(f)$$

Rearranging the terms on the right hand side and writing V_C for ε_S we get:

$$I_C = (2\pi f C)V_C \qquad \text{.........(12)}$$

This equation is usually rearranged as:

$$V_C = \left(\frac{1}{2\pi f C}\right) I_C$$

We define $1/(2\pi f C)$ as the *reactance* of the capacitor, (*capacitive reactance*, to be exact) and write χ_C for it. The unit of χ_C can be shown to be $(Js)/C^2$ (*).

Writing:

$$\chi_C = \frac{1}{2\pi f C} \qquad \text{.........(13)}$$

eqn (12) can be rewritten as:

$$V_C = \chi_C I_C \qquad \text{.........(14)}$$

Equations (12) and (13) are our equations for the behavior of capacitors in an AC circuit.

Objectives of the Experiment

To study: (1) the performance of a capacitor in a DC circuit,

(2) the pseudo conduction of a capacitor in an AC circuit.

Setting up

(1) The Performance of a Capacitor in a DC Circuit

One can set up the circuit of Fig (7), replacing the battery by a voltage control network (voltage divider circuit). This should be followed by selecting different voltages and monitoring the corresponding currents. What do you expect to find here? Do you think you will need to plot a graph?

(2) The Pseudo Conduction of a Capacitor in an AC Circuit

Recall Eqn. (11) $\qquad I_C = (2\pi f C)\ V_C$

The right hand side of the equation has three variables: (i) f (ii) C, and (iii) V_C. Hence the study must be made in three parts. In each part, two of the three variables will have to be kept constant; the third will be allowed to assume different values and the corresponding current values will be recorded. The three parts, therefore, are: (i) I_C *Vs* f (ii) I_C *Vs* C, and (iii) I_C *Vs* V_C. We shall require a source of AC voltage with variable output voltage and variable output frequency. We shall also require a capacitor with selectable capacitances.

One can set up the circuit of Fig (8), using a *Function Generator* as the source of AC electricity. Here both, the voltage and the frequency are independently selectable. Similarly, a *capacitance substitution box* will be used which allows us to select different capacitance values, over a wide range.

The linear dependence of capacitor current on each of the three variables should yield straight line graphs. Merely getting straight lines will be acceptable proof of the validity of the said equation. We may, however, find slopes in each case and work out their corresponding units. The expected values of the slopes can be calculated and compared with those found experimentally. Reasonable agreements will greatly enhance our confidence in the validity of Eqn (11).

(*) The unit of reactance, $(Js)/C^2$, is also the unit of electrical *resistance* and is called *ohm*. We write Ω for it. For this reason, reactances are described and measured in *ohms.*

Capacitors & Leakage Resistances

Almost all commercially available capacitors are far from being ideal capacitors. The imperfection is due to the inability of the capacitor to hold *all* the charges that it is supposed to hold. This inability is conveniently expressed in terms of a *leakage resistance*. We assume that the capacitor has a built in high resistance and that some charges manage to reach the opposite plate through this resistor where they neutralize an equal amount of opposite charges.

This departure from being perfect is noticeable significantly in the study of $I_C \;\; Vs \;\; f$. Here one gets a slightly curved line instead of a straight line. This is a non-linear response. The departure from linearity is small and may be treated as a *second order effect*. One way of eliminating a second order effect is to fit a *second order polynomial* curve instead of a *simple* straight line for the data obtained in the laboratory. Instead of using: $y = b + mx$, one would use:

$$y = b + mx + m'x^2 \qquad \text{.........(15)}$$

The value of m as found from Eqn (14) should now match the expected slope.

Procedure

(A) The Performance of the Given Capacitor in a DC Circuit

(1) Set up the circuit shown in Fig (10).

(2) Select a 1.00 μF capacitor in the *capacitance substitution box*.

(2) Use one multimeter as a voltmeter and set it to 20 V, DC.

(3) Use the second multimeter as an ammeter and set it to 200 mA, DC.

(4) Switch on the circuit in the following order: (a) DC supply, (b) voltmeter, (c) ammeter.

(4) For 10 arbitrary position of the sliding contact of the rheostat (covering the entire length of the rheostat), record the voltmeter and ammeter readings and enter in the Data Table.

(5) This is the end of the first part.

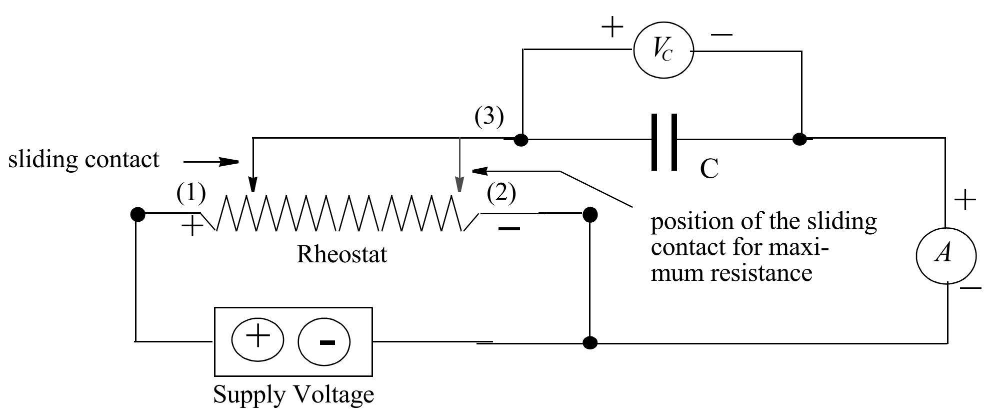


Fig (10) The Study of the Performance of a Capacitor in a DC Circuit.

(B) The study of the Pseudo Conduction of the Given Capacitor

Set voltmeter to 200 V AC and the ammeter to 20 mA AC. Set the supply voltage (from the function generator) to 5.0 volts, using the amplitude control knob. Make sure the generator waveform is set to *sine* waves.

(a) Dependence of capacitor current I_C on frequency f of the AC source

(1) Set up the circuit shown in Fig (11), using function generator, rheostat, capacitance box and two multimeters.

(2) Select a 0.05 μF capacitor on the *capacitance substitution box*.

(3) We shall select 21 values of frequency f for the AC supply. These will range from 500 Hz to 1500 Hz in steps of 50 Hz. These frequencies will be selected on the digital function generator. Note that frequency can only be selected by using the frequency control knob of the function generator.

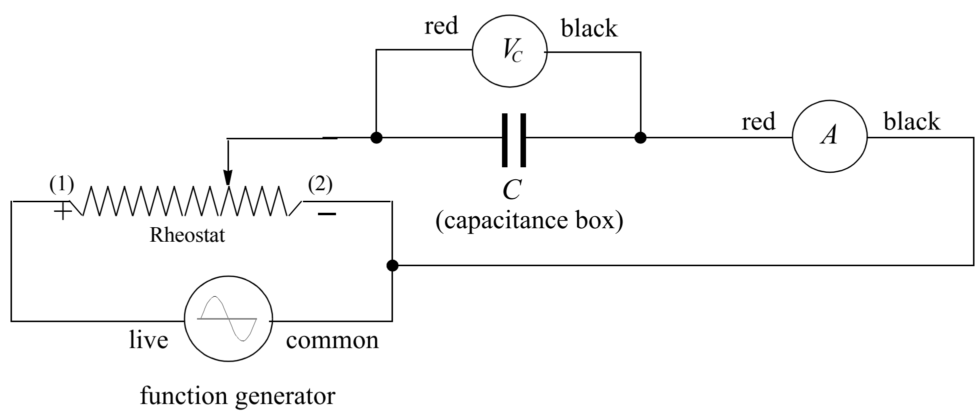


Fig (11) Circuit Diagram for the Study of Pseudo Conductance

(4) Switch on the circuit in the following order: (a) function generator (b) voltmeter, and (c) ammeter.

(5) Select the frequencies, one by one and for each frequency, adjust the position of the sliding contact of the rheostat, (if necessary) to set the capacitor voltage V_C **equal to 3.00 volts exactly** (to two decimal places). Read and record the current (in mA) as shown by the ammeter.

(b) Dependence of capacitor current I_C on capacitance C

(6) Set the frequency to 1.0 kHz for the second and third parts of the experiment. There is no need to switch off the circuit.

(7) Select capacitors of the following values: 0.005 μF, 0.01 μF, 0.015 μF........0.10 μF.

(8) For each capacitor, make sure that the AC source voltage is 3.0 V, exactly, to two decimal places. Adjust, if warranted. Read and record the current (in mA) as shown by the ammeter.

(c) Dependence of capacitor current I_C on capacitor voltage V_C.

(9) Select a 0.05 μF. capacitor. Make sure that the frequency of the AC source is 1.0 kHz. Set the sliding contact of the rheostat for maximum or near-maximum resistance (near-minimum voltage).

(10) For 16 arbitrarily chosen positions of the sliding contact (not necessarily at equal distances), read and record the voltages and currents, as shown by the meters.

(11) The experiment ends. Switch off in reverse order (see step 4 of section B). Disconnect the circuit and arrange all apparatus neatly on the table.

Calculations & Graphs

(A) The Performance of the Given Capacitor in a DC Circuit

Students should do what *they* think they should do.

(B) The study of the Pseudo Conduction for the Given Capacitor

(1) We shall be plotting 3 graphs. In each graph, I_C (in mA) will be plotted on the y-axis. For the first graph, x-axis will have frequency f (in kHz). This graph must be fitted with a second order polynomial curve. For the second graph, x-axis will have capacitance C (in μF); and for the third graph, x-axis will have capacitor voltage V_C, (in volts). A *simple* straight line fit should be obtained for these two graphs. Read and record the slopes for each graph, as printed out by the computer.

(2) Correct each slope value for units. The slope of each of the three graphs will have to be multiplied by 10^{-3} to convert milliamperes to amperes. Additionally, the slope of the first graph must be divided by 10^3 to convert kHz to Hz. The slope of the second graph will have to be divided by 10^{-6} to convert microfarads to farads. The slope of the third graph does not need additional treatment.

(3) Find the reactance, χ_C of the capacitor as the reciprocal of the slope of the third graph.

(4) Calculate the expected values of the slope in each case, making sure that you use correct MKS units. For example 2.0 kHz = 2.0 x 10^3 Hz, and 0.05 μF = 0.05 x 10^{-6} F. Compare the expected and the experimental values of the three slopes and find percent errors.

Calculating the expected values:

(5) (a) For dependence of I_C on f, the constant of the equation is $2\pi C V_C$. The unit is charge Q in coulombs. Calculate its value. This is the expected value for this dependence and should be compared to the slope of the first graph.

(b) For dependence of I_C on C, the constant of the equation is $2\pi f V_C$. The unit is volts per second or V/S. Calculate its value. This is the expected value for this dependence and should be compared to the slope of the second graph.

(c) For dependence of I_C on V_C, the constant of the equation is $2\pi f C$. The unit is *mho* or Ω^{-1}. Calculate its value. This is the expected value for this dependence and should be compared to the slope of the third graph.

(6) Calculate the reactance χ_C (in ohms), of the given capacitor using Eqn (12). The values of f and C are those used for the study of I_C *vs.* V_C. This is the expected value of χ_C. Compare with the experimental value and find percent error.

(7) For your convenience, a table of "Results" is provided on page 39.

Conclusions and Discussions

Write your conclusions from the experiment and discuss them.

What Did You Learn in this Experiment?.

A hearty and thoughtful account of what you learned in this experiment by way of the principle and the techniques of experimentation, should be given

Data & Data Tables

Name.................................. **Date**............................
Instructor............................ **Lab Section**...................
Partner.......................... **Table #**.........................

(A) The Performance of Capacitors in a DC circuit.

Voltmeter scale set to: (V)
Ammeter scale set to: (mA)
Capacitance Substitution Box set to: (μF)

Table 1: I_C Vs. V_C Investigation

Serial Number	Capacitor Voltage: V_C (V)	Capacitor Current: I_C (mA)	Serial Number	Capacitor voltage: V_C (V)	Capacitor Current: I_C (mA)
1			6		
2			7		
3			8		
4			9		
5			10		

Additional data or information, if any:

(B) The Study of the Pseudo Conduction of the Given Capacitor.

(a) Dependence of capacitor current I_C on the frequency f of the AC source.

Voltmeter scale set to: V

Ammeter scale set to: mA

Voltage output of the function generator V_s set to: V

Capacitance Substitution Box set to: 0.05 μF

Capacitance value as found using LCR meter: μF

Capacitor voltage V_C set to: 3.00 V

Table 2: I_C Vs. f Investigation

Serial Number	Frequency f	Capacitor Current: I_C (mA)	Serial Number	Frequency f	Capacitor Current: I_C (mA)
1	500 Hz		12	1050 Hz	
2	550 Hz		13	1100 Hz	
3	600 Hz		14	1150 Hz	
4	650 Hz		15	1200 Hz	
5	700 Hz		16	1250 Hz	
6	750 Hz		17	1300 Hz	
7	800 Hz		18	1350 Hz	
8	850 Hz		19	1400 Hz	
9	900 Hz		20	1450 Hz	
10	950 Hz		21	1500 Hz	
11	1000 Hz				

(b) Dependence of capacitor current I_C *on capacitance,* C.

Frequency of the function generator set to: 1.00 kHz

Voltage output of the function generator set to: 3.00 V

Table 3: Data for I_C **Vs.** C **Investigation**

Serial Number	Capacitance C (μF)	I_C (mA)	Serial Number	Capacitance C (μF)	I_C (mA)
1	0.005		11	0.055	
2	0.010		12	0.060	
3	0.015		13	0.065	
4	0.020		14	0.070	
5	0.025		15	0.075	
6	0.030		16	0.080	
7	0.035		17	0.085	
8	0.040		18	0.090	
9	0.045		19	0.095	
10	0.050		20	0.100	

(c) Dependence of capacitor current I_C *on capacitor voltage,* V_C.

Capacitance Substitution Box set to: 0.05 μF

Frequency of the function generator set to: 1.00 kHz

Table 4: Data for I_C **Vs.** V_C **Investigation**

Serial Number	Capacitor Voltage: V_C (V)	Capacitor Current: I_C (mA)	Serial Number	Capacitor voltage: V_C (V)	Capacitor Current: I_C (mA)
1			9		
2			10		
3			11		

Table 4: Data for I_C **Vs.** V_C **Investigation**

Serial Number	Capacitor Voltage: V_C (V)	Capacitor Current: I_C (mA)	Serial Number	Capacitor voltage: V_C (V)	Capacitor Current: I_C (mA)
4			12		
5			13		
6			14		
7			15		
8			16		

Results Table **Name** **Date**

Results ***Capacitors in DC & AC Circuits***

(A) DC Circuit:

Dependence of Capacitor Current I_C on Capacitor Voltage V_C

(B) AC Circuit:

(a) Dependence of capacitor current I_C on the frequency f of the AC source.

Relationship of I_C to f

	expected value	experimental value	% error
the magnitude of charge (C)	(C)	(C)	

(b) Dependence of capacitor current I_C on capacitance, C.

Relationship of I_C to C

	expected value	experimental value	% error
voltage per second (V/S)	(V/S)	(V/S)	

((c) Dependence of capacitor current I_C *on capacitor voltage,* V_C

Relationship of I_C to V_C

	expected value	experimental value	% error
pseudo-conductance Ω^{-1}	Ω^{-1}	Ω^{-1}	

(d) The Reactance χ_C *of the Given Capacitor at* $1.0kHz$

Reactance χ_C of the Given capacitor

	expected value	experimental value	% error
reactance χ_C, (Ω)	(Ω)	(Ω)	