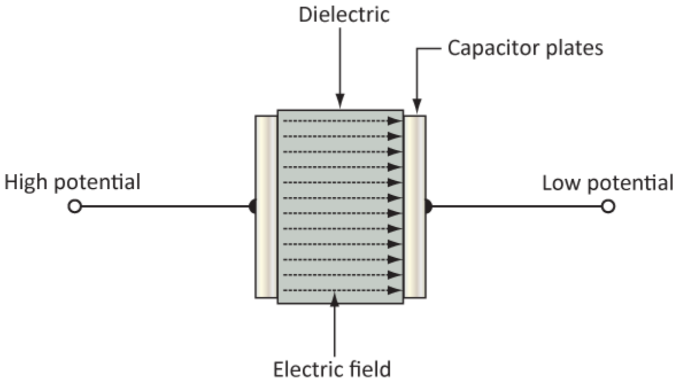
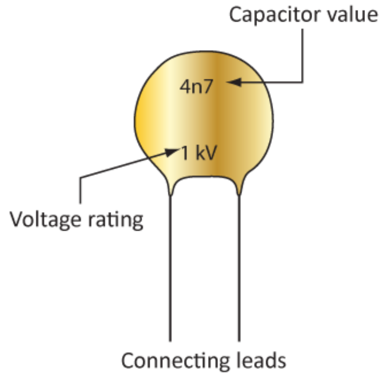
Level 3 Diploma
in
Installing Electrotechnical Systems & Equipment

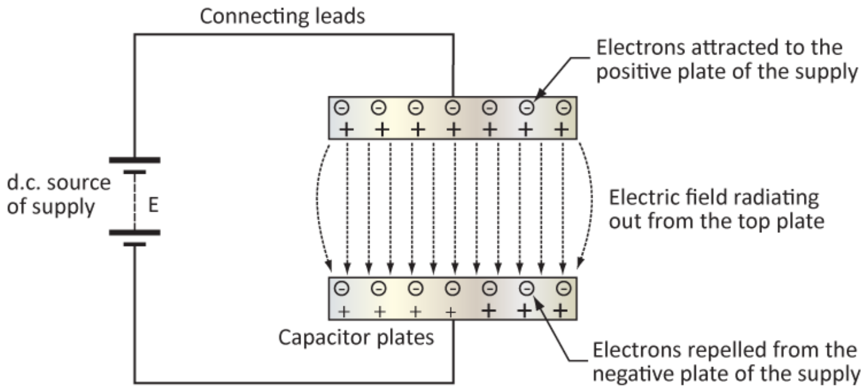
associates ltd

C&G 2357

Unit 309-7A Understand the operating principles and applications of capacitors.







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Aims and objectives

By the end of this study book you will have had the opportunity to:

- describe what capacitors are
- define various terms such as electrical field, stress, dielectric, and charge
- highlight construction of various types, in particular the parallel plate and air-spaced
- comment upon the dangers associated with capacitors and capacitance.

1: Electrostatics and basic capacitance

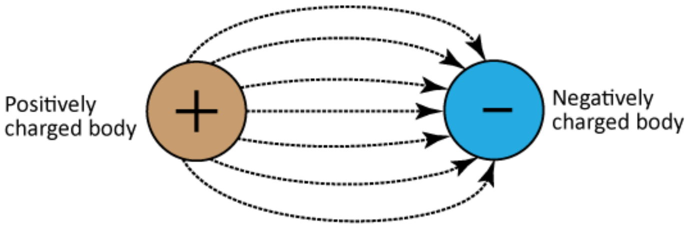
In this session the student will:

- Describe what basic capacitance is.
- Describe electric lines of flux
- Describe the operation of a capacitor connected to an a.c. supply

Basic capacitors

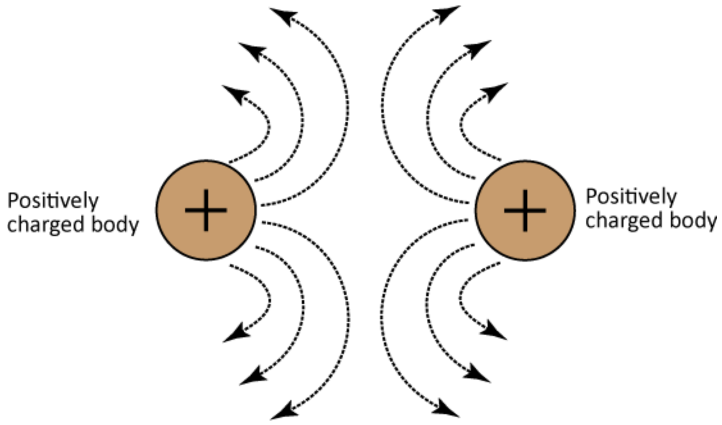
Quite simply a capacitor is a device used to store an electric charge – it is a storage device. This section will consider how that storage is able to occur.

Surrounding any electrical charge, whether it is a positive or a negative charge, there is a field. This field is an area that is affected electrically by that particular charge.



Electric field between two oppositely charged bodies

Similar to the situation with magnetic fields where like poles repel, (north to north or south to south) and unlike poles attract (north to south), an electrical charge attracts and repels. If there are two positive charges then they will repel each other. If there are two negative charges then they will repel each other.

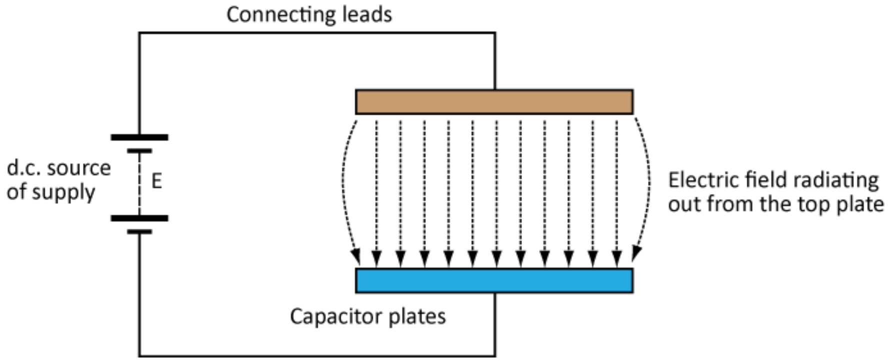


Electric field between two similarly charged bodies

If an object loses electrons then it will have a positive charge. If an object gains electrons then it has a negative charge. You can get some idea of charge and attraction when you try rubbing a balloon on your jumper and then holding it against a wall. You find that the balloon remains stuck to the wall. The difference in charge leads to attraction of the balloon to the wall.

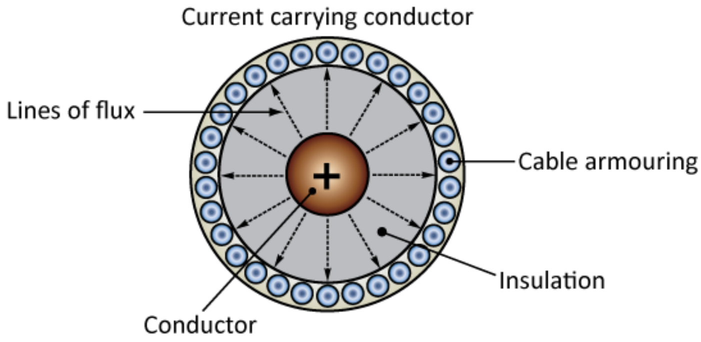
The lines shown above are called lines of '**electric flux**', and they are the lines that the charge would move along if it were free to travel.

In the diagram below and over the page there are two instances where there is an attraction.



In this instance, we have the two plates of a capacitor that have been charged up. The lines of flux shown represent the path that a charge would follow if it could. It is the charge therefore that is being attracted from one plate to the other.

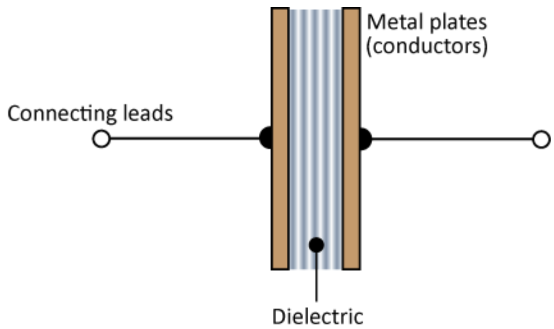
Below a conductor has a charge and the cable armouring has a different charge. The charge path that the lines represent radiate out from the centre like the spokes of a wheel.



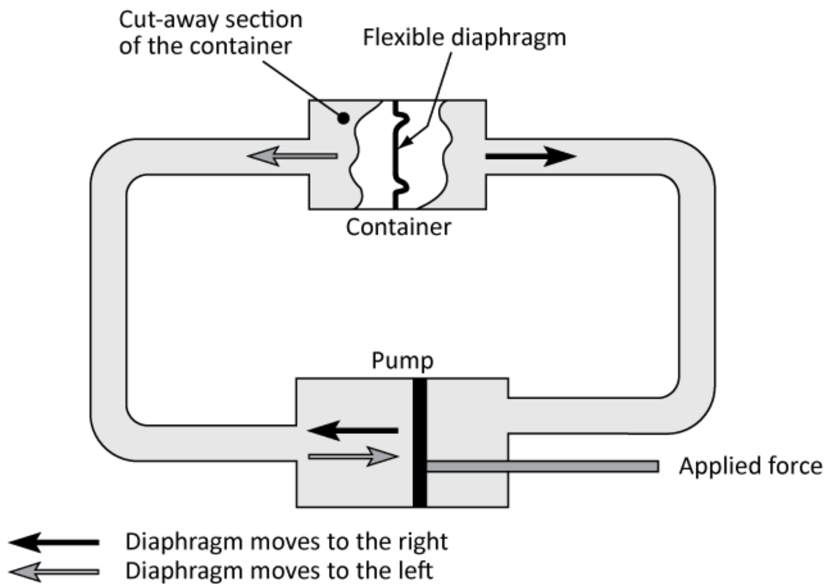
These effects can be seen if a large voltage (several thousand volts, kV) is applied across the plates of a capacitor, and mica dust is sprinkled over the top.

The same attraction is taking place however as with the plates on the previous page. The charge is being attracted.

A capacitor is a device made up of two conductive plates separated by an insulator. The diagram below shows how a capacitor is made up.



There is a mechanical analogy to how the capacitor works. Try to follow it with me.



Imagine that we have a system filled with a fluid. There is the ability for the fluid to have a force applied to it via the pump.

If a force is applied to the system from left to right, then fluid is forced around the system, and the diaphragm in the container bends and the right-hand chamber contains more fluid.

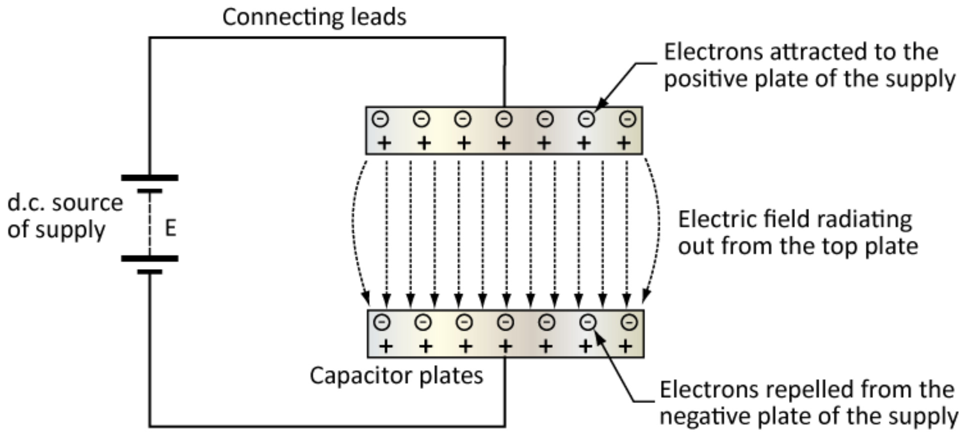
If the pump moves towards the left, then the diaphragm in the container moves and there is more fluid in the left-hand chamber.

There are two thoughts that should strike you immediately.

- A capacitor will only charge up when d.c. is applied and after that no more current will flow. Which is precisely what happens, and this principle is made use of in filter circuits for amplifiers in electronics.
- When an a.c. supply is connected then the capacitor will be constantly charging and discharging. This also means that the energy stored in the capacitor on the initial charge will be 'given back' to the supply.

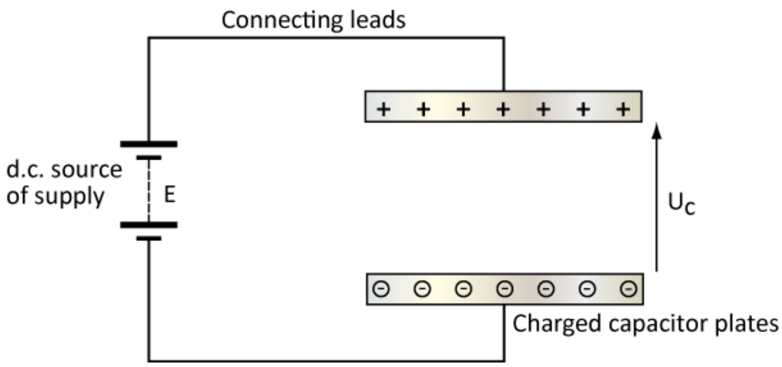
A capacitor doesn't have a diaphragm, but when we apply a d.c. voltage across it then a positive charge appears on one side of the plate and a negative charge on the other plate.

Try to follow this electrically now. When a d.c. supply is connected to a capacitor there is a separation of charge.



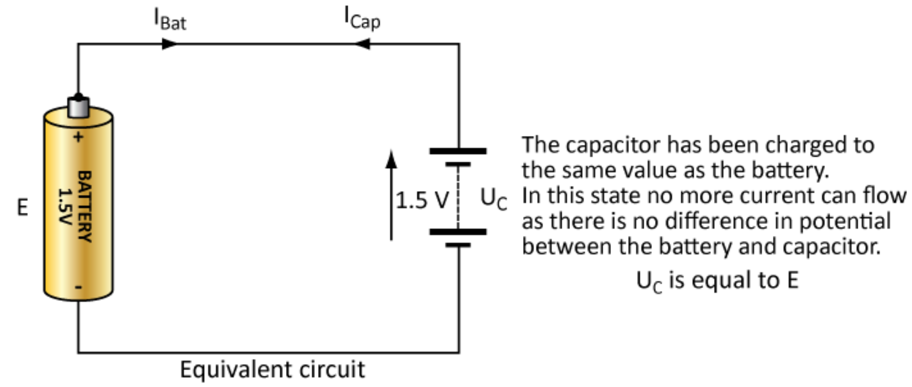
Above the battery or cell is connected to the capacitor. The positive of the battery attracts the **negative** charges (electrons). At the same time, the negative of the battery attracts the **positive** charges.

This process has the effect of leaving a positive charge on the capacitor plate connected to the positive terminal of the battery, and leaves a negative charge on the other capacitor plate that has been connected to the negative terminal of the battery.



You can see that the positive charges are all on one side, connected to the positive side of the battery or cell. The negative charges have all been gathered together on the other side of the capacitor and are connected to the negative of the battery or cell.

This can be described another way.

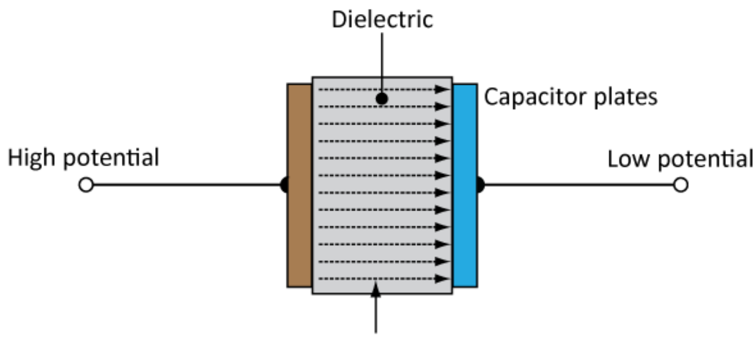


Equivalent circuit

Here we have the equivalent circuit of a capacitor connected to a battery. It is as if we have two batteries connected together with their two positive sides connected together and their two negatives connected together. The battery emf eventually ends up as the potential across the plates of the capacitor.

With an a.c. supply, things alter somewhat. This occurs because the supply is constantly changing (alternating) and therefore the charge on the capacitor plates is swapping about every half-cycle (50 Hz or 50 times per second).

Electric flux



Above we can see the ***electric field*** that appears across the dielectric (insulator) between the two plates of a capacitor when a d.c. supply is connected across it.

This '***field***' is described using the lines that appear across the dielectric. They don't really exist but they do help us to picture what is happening.

As I have already stated, these imaginary lines follow the path that a charge would take, if it were possible, through the dielectric. They are not necessarily straight lines but they do not cross each other. You can see that there must be a difference in potential between these two plates.

The measure of the electric field strength is called the ***electric flux*** or ***charge***. Electric flux has a unit and a symbol.

Unit *C* (coulomb)
Symbol *Q*

The dielectric is an insulator and therefore has a very high resistance. However, the dielectric does allow the electric flux to be generated.

Exercise 1.

1) In basic terms, what is a capacitor?

2) Explain how the plates on a capacitor become charged.

3) What is electric charge measured in, and what is its symbol?

4) What would happen to the current flow in a d.c. circuit when the capacitor is fully charged? Can you explain why this happens?

5) Will a length of two-core cable have capacitance? Why is this the case?

Now move on to the next session.

2: Capacitance

In this session the student will:

- Gain an understanding of the factors affecting capacitance.
- Gain an understanding how energy is stored in a capacitor.

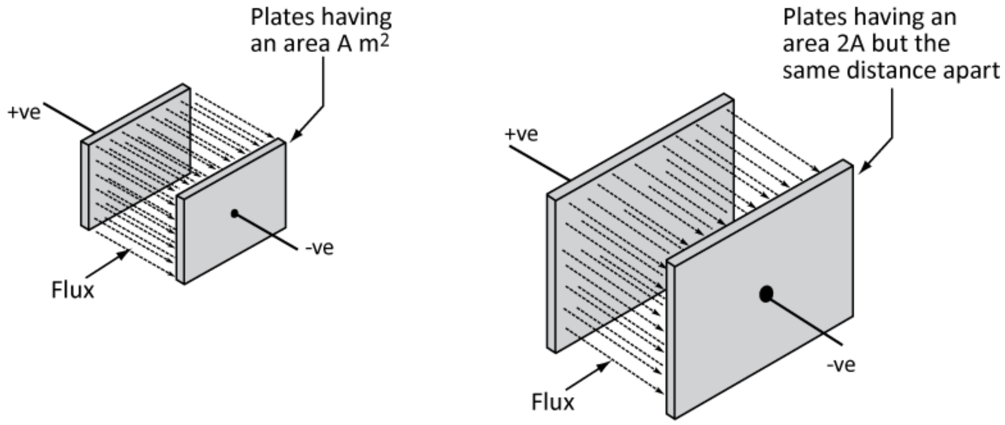
In the first session we saw that a capacitor is made up of two conductors (plates) separated by an insulator (dielectric).

We also saw that a capacitor sets up an electric field. This field is pictured as a series of straight lines running between the two plates. The lines are the path that an electric current would flow along if it were able.

In this session we are going to deal in some detail with how we define capacitance itself.

Electric flux density

When the electric flux passes through a certain area then we can determine the ***electric flux density***.



With more lines of electric flux, the flux density will be much greater.

Equally with an increase in area, there is a corresponding reduction in flux density (same number of lines over a greater area).

Electric flux density has a unit and symbol.

Unit C/m^2 or Cm^{-2} (coulomb per metre^2)

Symbol D

As you would expect there is a formula for this.

$$\text{Electric flux density} = \frac{\text{Electric flux}}{\text{Area}}$$

$$D = \frac{Q}{A}\text{Cm}^{-2}$$

Try a couple of examples before we move on.

1). Calculate the charge stored by a parallel-plate capacitor if the electric flux density is 25 mC/m^2 and the area of each plate is 650 mm×650 mm.

$$D = \frac{Q}{A} \quad \text{transpose}$$
$$Q = DA$$
$$A = lb = 650 \times 650 = \underline{\underline{422500\text{mm}^2}} = \underline{\underline{0.4225\text{m}^2}}$$
$$Q = 25 \times 10^{-3} \times 0.4225 = \underline{\underline{0.01056\text{C}}} = \underline{\underline{10.56\text{mC}}}$$

You should notice that the values all have to be converted to their base units. Millimetres to metres etc. Don't take any short cuts!

2). A capacitor has a charge of 40 µC. If the area of the plates of the capacitor are 5 cm^2 what is the flux density?

$$D = \frac{Q}{A}$$
$$D = \frac{40 \times 10^{-6}}{5 \times 10^{-4}} = \underline{\underline{0.08\text{Cm}^{-2}}} = \underline{\underline{80\text{mCm}^{-2}}}$$

Again, notice that the values have been put into their base units. This time it was centimetres to metres. As a guide, there are 10 000 cm^2 in 1 m^2, and there are 1 000 000 mm^2 in 1 m^2.

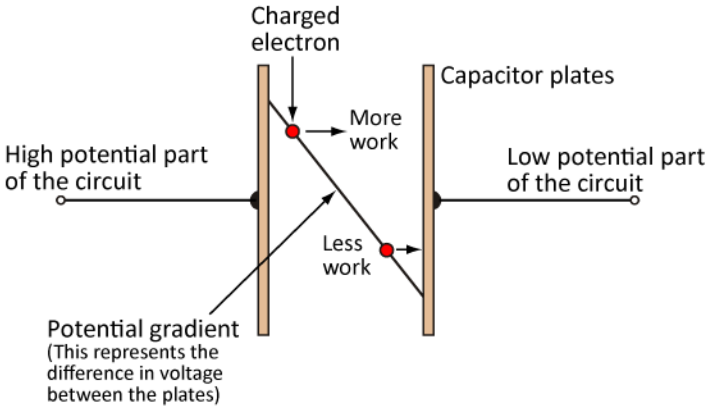
During this study book, you are going to come across a large number of formulae. I will state them as we go along, and they are also listed at the end of this study book. However, you should try to memorise them.

Electric field strength, permittivity and energy

We've looked at electric flux and electric flux density. We're now going to take a look at the **electric field strength**.

The electric field strength has a number of other names, such as ***electric field intensity***, ***potential gradient*** and ***electric stress***.

When there is a difference in potential between the two plates of the capacitor then 'work' is done on a charge. The force that is applied to the charge is called the ***electric field strength***.



Above we can see that there is a positive charge on one plate with a negative charge on the other.

A voltage is applied to the plates and the plates are a certain distance apart (the distance varies according to the type of capacitor but is in the region of µm (micro-metres) to mm).

The gradient shown in the diagram represents the fall off in voltage that occurs on the charge as it tries to pass through the dielectric. Remember that we are dealing with what would happen to an electron if it '**could**' drift across the dielectric-in a perfect capacitor.

Electric field strength has units and a symbol. You should not however get the symbol for field strength and emf mixed up even though they are both ***E***.

Unit V/m or Vm^{-1} (volts per metre)

Symbol E

The force experienced by the charge depends on two things. These are:

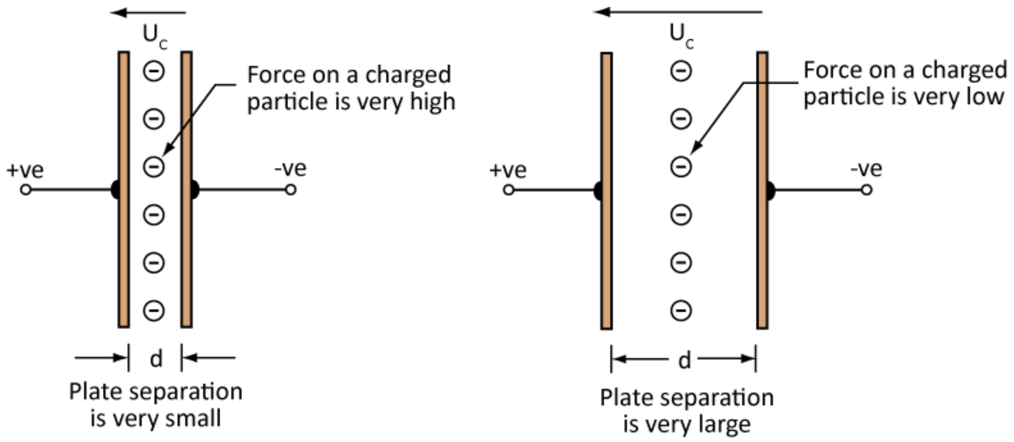
- The voltage applied
- The distance that the plates are apart.

As you would expect there is a formula.

$$\text{Electric field strength} = \frac{\text{Volts}}{\text{Distance}}$$

$$E = \frac{U_\text{C}}{\text{d}}\,\text{Vm}^{-1}$$

The distance between the two plates of a capacitor is very small. This means that the field strength is high. The natural consequence of this is that the force applied to a charge is high. If we were to increase the distance between the plates then we would decrease the force on the charge.



Have a look at a couple of examples and see what this means.

1). A capacitor has a supply of 9 V connected across it. The thickness of the dielectric is 0.03 mm. What is the electric field strength?

$$E = \frac{U_\text{C}}{\text{d}}$$

$$E = \frac{9}{0.03 \times 10^{-3}} = \underline{\underline{300000\text{Vm}^{-1}}} = \underline{\underline{300\text{kVm}^{-1}}}$$

Notice that the millimetres have been converted to metres. You should also notice just how large the figure is. Further reduce the distance and you will dramatically increase the electric field strength.

2). The same capacitor used in the question 1 has the thickness of its dielectric increased to 0.5 mm. What will be its new electric field strength?

$$E = \frac{U_c}{d}$$

$$E = \frac{9}{0.5 \times 10^{-3}} = \underline{\underline{18000\text{Vm}^{-1}}} = \underline{\underline{18\text{kVm}^{-1}}}$$

Notice the very large reduction in the electric field strength.

3). A capacitor has plates 0.15 mm apart. If the electric field strength is 0.975 kV/m what will be the voltage need to be?

$$E = \frac{U_c}{d} \quad \text{transpose}$$

$$U_c = Ed$$

$$U_c = 0.975 \times \cancel{10^{3}} \times 0.15 \times \cancel{10^{-3}}$$

$$U_c = 0.975 \times 0.15 = \underline{\underline{0.146\text{V}}}$$

Again, the millimetres have been changed to metres.

Don’t take any short cuts, even if you think that these appear straightforward. Mistakes happen.

There is a relationship between the ‘***flux density***’ that we have already looked at, and the ‘***electric field strength***’.

The permittivity of a material is a measure of its ability to allow electric flux to be established.

This relationship is called the ***permittivity*** or ***absolute permittivity***. A definition is given below.

Unit F/m or Fm^{-1} (Farad per metre)

Symbol ε

There is, as you would expect, a formula, unit and symbol for this.

'Permittivity' or 'absolute permittivity' is made up of the ***permittivity of free space*** and the ***relative permittivity***.

$$\text{Permittivity} = \frac{\text{Electric flux density}}{\text{Electric field strength}}$$

$$\varepsilon = \frac{D}{E}\text{Fm}^{-1}$$

It has been found experimentally that the permittivity of a vacuum (free space) is $8.85 \times 10^{-12} F/m$. The unit is the same as for absolute permittivity but the symbol is ε_0 (epsilon nought). Essentially, the permeability of a vacuum is the same as that for air.

The relative permittivity is a measure of how much better a dielectric is compared to permittivity of free space. This allows us to compare the relative strengths of different dielectrics.

Have a look at the table below and see some of the known values.

Material	Relative permittivity
Vacuum	1.0
Air	1.0006
Paper	2-2.5
Polythene	2-2.5
Rubber	3
Insulating oil	4
Bakelite	7
Mica	5
Porcelain	6
Glass	7.5
Distilled water	80
Barium-strontium titanite	7 500

You can see from this table that air and a vacuum are very close.

So paper as a dielectric at a relative permittivity of 2, will be able to have twice as much electric flux established in it compared to air.

You will also see that pure, distilled water is an excellent insulator. The impurities in water make it a conductor. Pure water is a very poor conductor.

So, what is the relationship between absolute permittivity, relative permittivity and the permittivity of free space?

$$\text{Absolute permittivity} = \text{Relative permittivity} \times \text{Permittivity of free space}$$

$$\varepsilon = \varepsilon_{\mathrm{r}}\varepsilon_0 \quad \text{transpose}$$

$$\varepsilon_{\mathrm{r}} = \frac{\varepsilon}{\varepsilon_0}$$

We have looked at electric field strength, electric flux, electric flux density and permittivity. We now need a definition of what **capacitance** is. We have looked at how charges are set up and the forces that apply to that charge. We have looked at some of the factors that affect a capacitor, but we don't have a definition of what capacitance is. So here goes!

- Capacitance is a measure of the ability of the capacitor to store energy.
- A capacitance of one farad stores a charge of one coulomb when one volt is applied between its plates.

Therefore, a capacitor stores energy and capacitance is a measure of how well the capacitor stores that energy.

A capacitance of one farad (1F) is really quite large. There are some capacitors that have such large capacitances, but not many. Most capacitors are measured in micro-farads (***µF***=$\times 10^{-6}$) ; nano-farads (***nF***=$\times 10^{-9}$) or even pico-farads (***pF***=$\times 10^{-12}$). For example, the capacitor found in a fluorescent fitting would have a capacitance of approximately 9µF.

Our definition can be put into an equation.

$$\text{Capacitance} = \frac{\text{Electric flux}}{\text{Voltage across plates}}$$

$$C = \frac{Q}{U_{\mathrm{C}}}\mathrm{F}$$

Before we begin to look at a few examples, we can look at combining all the elements of what we have learnt into one equation.

Try to follow the creation of this formula carefully.

$$D = \frac{Q}{A} \quad \text{and} \quad E = \frac{U_c}{d}$$

$$\varepsilon = \frac{D}{E} \quad \text{so substitute}$$

$$\varepsilon = \frac{Q}{A} \div \frac{U_c}{d} \quad \text{invert and multiply for fractions}$$

$$\varepsilon = \frac{Q}{A} \times \frac{d}{U_c} = \frac{Qd}{AU_c} \quad \text{but } C = \frac{Q}{U_c}$$

$$\varepsilon = \frac{Cd}{A} \quad \text{and as } \varepsilon = \varepsilon_0 \varepsilon_r$$

$$\varepsilon_0 \varepsilon_r = \frac{Cd}{A} \quad \text{transpose for } C$$

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d}$$

This seems to be very long and complex, but it tells us is that the capacitance of a capacitor is related to the permittivity of free space (ε_0), the permittivity of the dielectric (ε_r), the area of the plates (A) and the distance between them (d).

We're now going to work through some examples. These should make apparent where everything fits in. Make sure that you take the time to follow the processes involved, rather than just jumping right in. We'll be making use of all the formulae that we have covered so far.

1). The area of the plates of a capacitor is 75 mm×3 m. The thickness of the dielectric is 0.25 mm. Assuming that the supply is 250 V d.c. and the relative permittivity is 5, determine the following:

i) The capacitance

ii) The charge stored in the capacitor

iii) The electric field strength.

Before we begin, it is worthwhile stating what you already know. Remember that the permittivity of free space is taken as 8.85×10^{-12}. Also, make sure that you convert everything to their base units.

i) The capacitance

$$A = lb = 3\times0.075 = \underline{\underline{0.225\text{m}^2}} P = I^2R$$

$$C = \frac{\varepsilon_0\varepsilon_r A}{d} = \frac{8.85\times10^{-12}\times5\times0.225}{0.25\times10^{-3}} = \underline{\underline{3.98\times10^{-8}\text{F}}} = \underline{\underline{39.8\text{nF}}}$$

ii) The charge stored in the capacitor

$$Q = CU_C$$

$$Q = 39.8\times10^{-9}\times250 = \underline{\underline{9.96\times10^{-6}\text{C}}} = \underline{\underline{9.96\mu\text{C}}}$$

iii) The electric field strength

$$E = \frac{U_C}{d}$$

$$E = \frac{250}{0.25\times10^{-3}} = \underline{\underline{1000000\text{V/m}}} = \underline{\underline{1\text{MV/m}}}$$

Notice the systematic approach. First, the area is found, then the capacitance; it is also worth noting that we only need to consider the area of one of the plates. Two plates do not create two charges; they create the ability for a charge to appear across them.

After this has been found, we can use our answer in the next section, where we can find the quantity of charge. The last two lines give us the electric field intensity.

2). A 12 µF capacitor has a plate area of 10 mm^2. The relative permittivity of the dielectric is 10. If the capacitor has a charge of 0.25 µC, calculate:

i) The electric flux

ii) The electric flux density

iii) The voltage across the plates

iv) The electric field strength.

Solution.

i) The electric flux, this was given in the question

$$\text{Flux} = \underline{\underline{0.25\mu\text{C}}}$$

ii) The electric flux density

$$D = \frac{Q}{A}$$

$$D = \frac{0.25 \times \cancel{10^{-6}}}{10 \times \cancel{10^{-6}}} = \underline{\underline{0.025\text{C/m}^2}} = \underline{\underline{25\text{mC/m}^2}}$$

iii) The voltage across the plates

$$Q = CU_C \quad \text{transpose}$$

$$U_C = \frac{Q}{C}$$

$$U_C = \frac{25 \times 10^{-3}}{12 \times 10^{-6}} = \underline{\underline{2083.3\text{V}}}$$

iv) The electric field strength.

$$\varepsilon = \frac{D}{E} \quad \text{transpose}$$

$$E = \frac{D}{\varepsilon} \quad \text{where } \varepsilon = \varepsilon_0 \varepsilon_r$$

$$E = \frac{25 \times 10^{-3}}{8.85 \times 10^{-12} \times 10} = \underline{\underline{282.5\text{MV/m}}}$$

When we consider parallel plate capacitors, things are a little different. These capacitors are variable and allow some variation in the capacitance value.

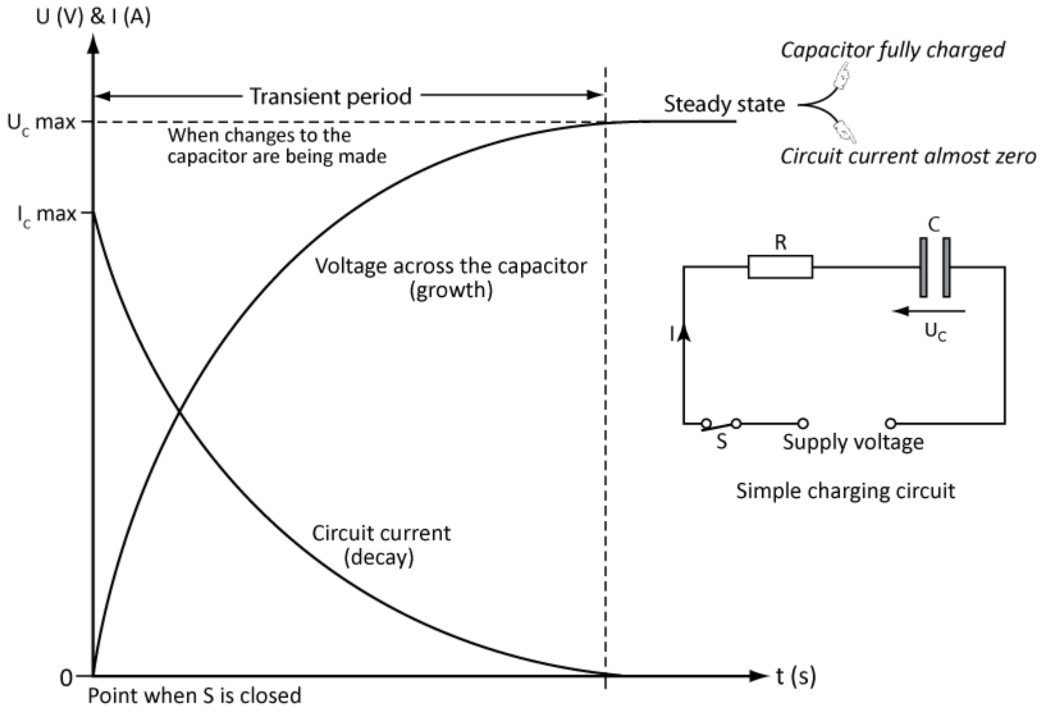
It is also worth noting that whenever a reasonable length of MI is insulation resistance tested, then a charge is often stored. The magnesium oxide is an excellent dielectric and the long length of conductors that run in the cable act as the plates of the capacitor.

Energy stored in a capacitor

When a capacitor is placed into a circuit and the circuit is then made live, the capacitor will start to charge. How fast it charges will depend upon what resistance is in the circuit as if you remember, resistance limits current flow.

As all circuits have resistance we can model the charging process by placing a resistor in series with the capacitor. When the circuit is first switched on the current will be at a maximum because the capacitor has no stored charge so there is nothing to oppose the supply voltage. This charging current will then start to reduce in value as the capacitor charges. As the voltage across the capacitor continues to rise, the circuit current will continue to fall until it almost reaches zero.

Have a look below. It shows how voltage and current change as a capacitor charges.



You'll notice that the two values are not straight lines but follow what is called an ***exponential curve***. There is a rapid rise of voltage across the capacitor matched by a steady fall of charging current until their respective maximum or minimum values are reached. We'll look at this in more detail later.

The energy stored in a capacitor is a relationship of voltage, current and time. Because there are exponential curves involved, everything becomes a little bit more complex. However, after all the maths has been done, an equation is finally reached.

W is the recognised symbol for energy and energy is always measured in ***joules***.

$$W = \frac{1}{2}CU^2 \quad \text{or} \quad W = \frac{CU^2}{2}$$

Have a look at examples done on the previous pages and see what the energy stored in the capacitors could be.

1). Considering the following examples:

a) Capacitance is 39.8 nF and the voltage is 250 V

$$W = \frac{1}{2}CU^2 = \frac{1}{2} \times 39.8 \times 10^{-9} \times 250^2$$
$$W = \underline{\underline{1.244 \times 10^{-3}\,\text{J}}} = \underline{\underline{1.244\,\text{mJ}}}$$

b) The capacitance is 12 µF and the voltage is 500 V

$$W = \frac{1}{2}CU^2 = \frac{1}{2} \times 12 \times 10^{-6} \times 500^2$$
$$W = \underline{\underline{1.5\,\text{J}}}$$

This value is very high and unlikely to occur in real life. However, as an exercise it proves the point.

c) Capacitance is 30.975 nF and the voltage is 750 V.

$$W = \frac{1}{2}CU^2 = \frac{1}{2} \times 30.98 \times 10^{-9} \times 750^2$$
$$W = \underline{\underline{8.713 \times 10^{-3}\,\text{J}}} = \underline{\underline{8.713\,\text{mJ}}}$$

In this last example, as with the first, you can see that very little energy is stored in capacitors of this size. Even very large capacitors don't hold that much energy. That is not to say that they cannot deliver a very large voltage.

Exercise 2.

1) What is electric charge measured in, and what is its symbol?

2) What is electric flux density measured in and what is its symbol? State the formula that describes it.

3) Calculate the charge stored in a capacitor if the electric flux density is 2.4 mC/m^2 and the area of each plate is 525 cm^2.

4) Define electric field strength and state its symbol, units and formula.

5) A capacitor has a supply of 45 V connected across it. The thickness of the dielectric is 0.002 mm. What is the electric field strength?

6) What is permittivity? State its symbol, units and formula.

7) Define capacitance, stating its unit and symbol. Also, state the two formulae that can be used to determine capacitance.

8) The area of the plates of a capacitor is 600 cm^2. The dielectric has a thickness of 0.1 mm and a relative permittivity of 4. If the supply voltage is 100 V determine the following:
   a) The capacitance
   b) The charge stored in the capacitor
   c) The electric field strength
   d) The energy stored.

3: Capacitors connected in parallel

In this session the student will:

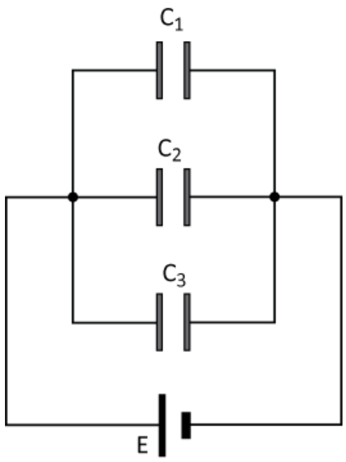
- Gain an understanding of how capacitors are connected in parallel.
- Gain an understanding of the effects of capacitors connected in parallel.

You have seen that a capacitor is a device that can store energy and that it stores this energy by separating electrical charge. On one of its plates when charged, it has an overabundance of negative charge; on the other plate, there is an overabundance of positive charge. This is when there is a d.c. supply.

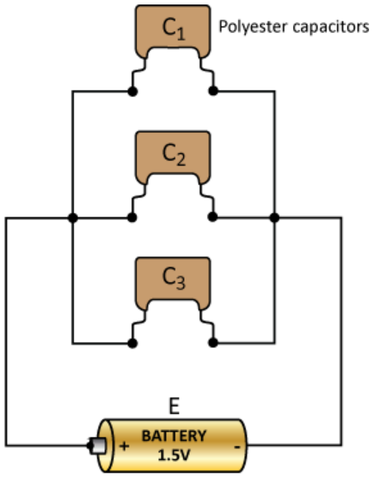
We now need to look at how these capacitors can be interconnected with each other and the effects that can and are produced.

Capacitors connected in parallel

Have a look below.



Circuit diagram



Wiring diagram

What we have here is a d.c. supply connected to three capacitors in parallel. That is each capacitor has the same supply.

We can start to make some basic assumptions therefore.

- The voltage dropped across each capacitor must be the same.

Same supply = Same voltage

There must be an increase in the level of capacitance.

We can increase the insulation properties of the dielectric;
We can increase the plate area;
We can reduce the distance that separates the two plates from each other.

You already know that there are three ways in which the level of capacitance can be increased.

When we are looking at capacitors in parallel, the total plate area must have increased and yet the distance between the plates has stayed the same. This naturally will increase the value of the capacitance.

Now, if the voltage dropped across each of the capacitors is the same, as it must be when connected in parallel, then the charge on each capacitor must add up to the total charge available.

$$U_S = U_1 = U_2 = U_3$$

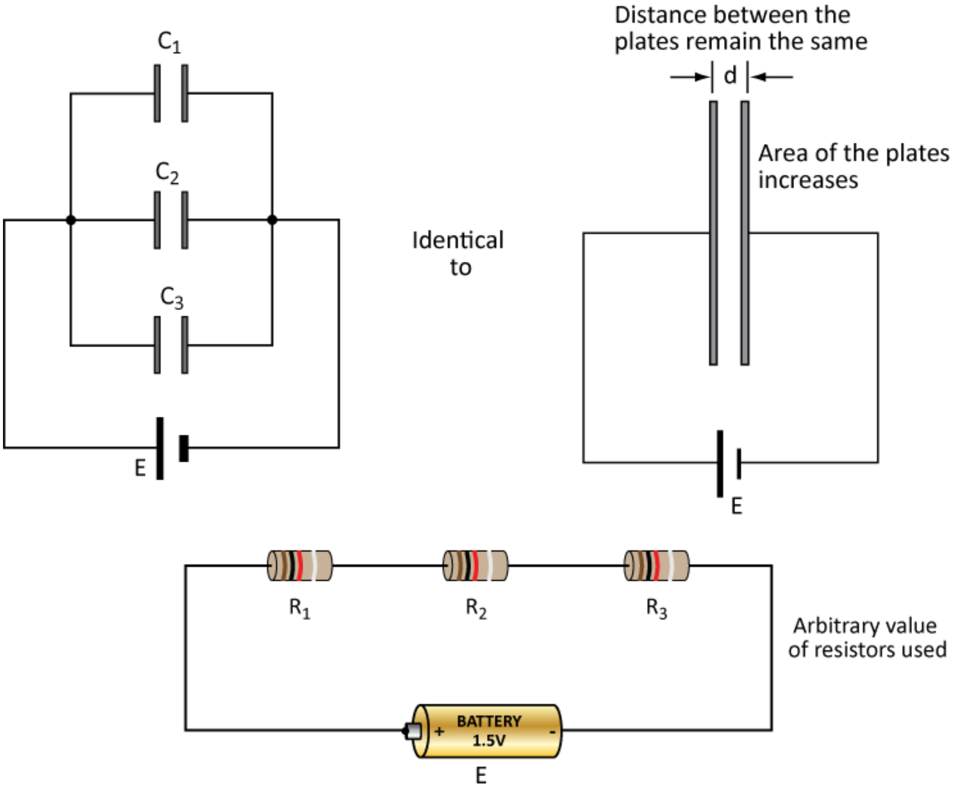
$$Q_T = Q_1 + Q_2 + Q_3$$

$Q = CU$ so substitute

$C_T \cancel{U_S} = C_1 \cancel{U_S} + C_2 \cancel{U_S} + C_3 \cancel{U_S}$ supply is common so can be cancelled

$$C_T = C_1 + C_2 + C_3$$

You can see here that when capacitors are connected in parallel, then we can determine the total capacitance just by adding up their values. This is the same as for resistors connected in series. Consider the diagram below showing the two examples side by side.

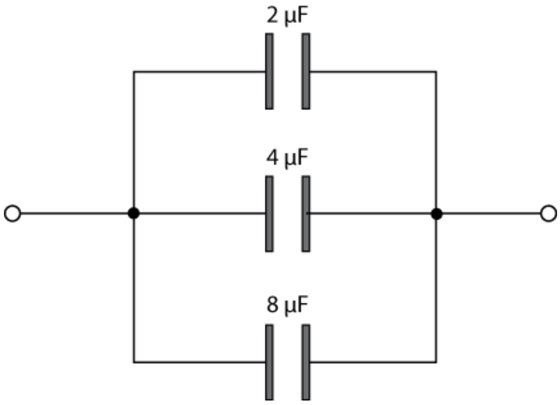


I hope that you can see the similarity.

The resistance is added because there is only one path for the current to take, whereas the capacitance is added because the effective plate area has increased.

1). Three capacitors valued at 2 µF, 4 µF and 8 µF are connected in parallel. Determine the total capacitance.

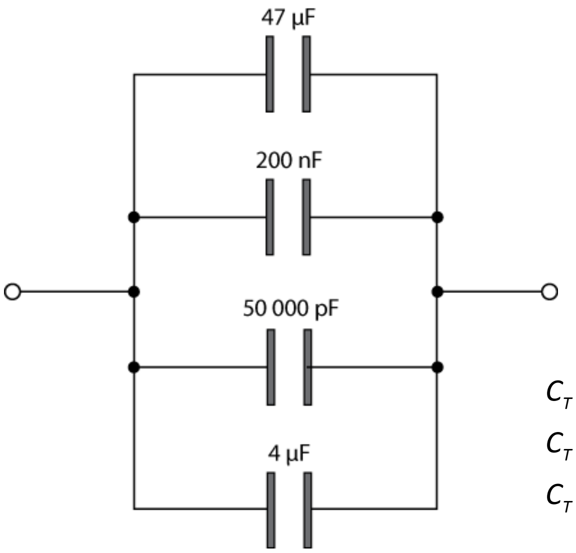
It is worthwhile doing a diagram.



$$C_T = C_1 + C_2 + C_3$$
$$C_T = 2\times10^{-6} + 4\times10^{-6} + 8\times10^{-6}$$
$$C_T = \underline{\underline{14\times10^{-6}\text{F}}} = \underline{\underline{14\mu\text{F}}}$$

Notice that there has been no short cut in the setting out of the problem. Don't just type things into your calculator, lay things out properly!

2). Four capacitors of values 47 µF; 200 nF; 50 000 pF and 4 µF are connected in parallel. What is the total value of capacitance?

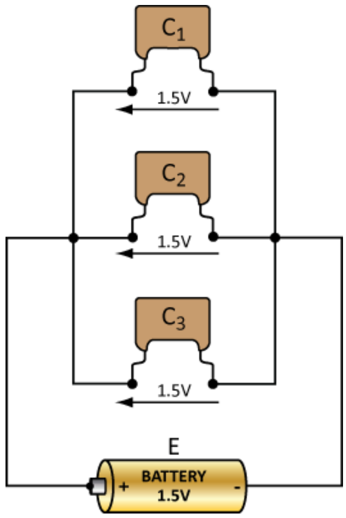


$$C_T = C_1 + C_2 + C_3 + C_4$$
$$C_T = 47\times10^{-6} + 200\times10^{-9} + 50000\times10^{-12} + 4\times10^{-6}$$
$$C_T = \underline{\underline{51.25\times10^{-6}\text{F}}} = \underline{\underline{51.25\mu\text{F}}}$$

The thing you have to be careful about here is making sure that you are using the same units throughout. Don't mix up nano-farads and pico-farads, there is a thousand times difference between the two. Take care over what you are doing.

Now that we have considered how to calculate the total value of capacitance, it is worthwhile spending a small amount of time considering the nature of voltage and charge.

We can see that when capacitors are connected in parallel then the voltage across all components will be the same. This is the same as with resistors connected in parallel.



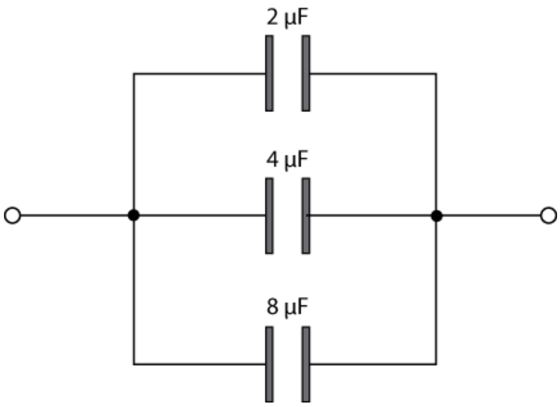
Now that we know the total voltage and the capacitance of each capacitor we can see that the total charge is the same as the charge of all the capacitors.

$$Q_T = Q_1 + Q_2 + Q_3$$

This means that we can determine the charge for each capacitor and if each capacitor has a different value then the charge will be different in each.

Let's consider our earlier examples.

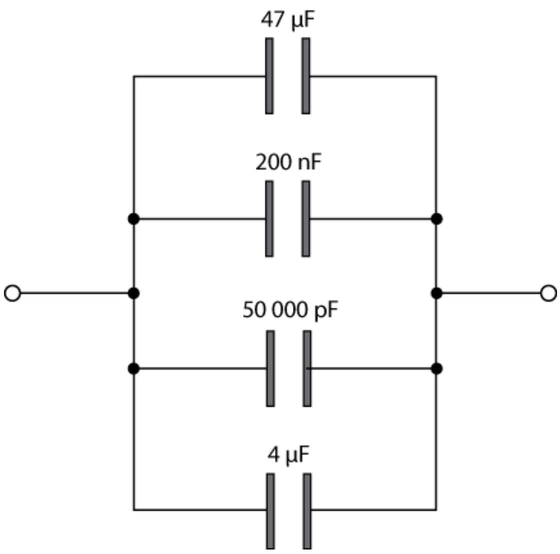
3). Three capacitors valued at 2 μF, 4 μF and 8 μF are connected in parallel. Determine the total capacitance and the charge in each capacitor if the voltage dropped across the network is 48 V.



$$C_T = C_1 + C_2 + C_3$$
$$C_T = 2\times10^{-6} + 4\times10^{-6} + 8\times10^{-6}$$
$$C_T = \underline{\underline{14\times10^{-6}\text{F}}} = \underline{\underline{14\mu\text{F}}}$$
$$Q = CU$$
$$Q_2 = 2\times10^{-6}\times48 = \underline{\underline{96\mu C}}$$
$$Q_2 = 4\times10^{-6}\times48 = \underline{\underline{192\mu C}}$$
$$Q_2 = 8\times10^{-6}\times48 = \underline{\underline{384\mu C}}$$
$$Q_T = CU = 14\times10^{-6}\times48 = \underline{\underline{672\mu C}}$$

Notice that there has been no short cut in the setting out of the problem. Don't just type things into your calculator, lay things out properly!

4). Four capacitors of values 47 μF; 200 nF; 50 000 pF and 4 μF are connected in parallel. What is the total value of capacitance and the charge in each if the supply voltage is 100 V?



$$C_T = C_1 + C_2 + C_3 + C_4$$
$$C_T = 47\times10^{-6} + 200\times10^{-9} + 50000\times10^{-12} + 4\times10^{-6}$$
$$C_T = \underline{\underline{51.25\times10^{-6}\text{F}}} = \underline{\underline{51.25\mu\text{F}}}$$
$$Q = CU$$
$$Q_{47} = 47\times10^{-6}\times100 = \underline{\underline{4.7mC}}$$
$$Q_{47} = 200\times10^{-9}\times100 = \underline{\underline{20\mu C}}$$
$$Q_{47} = 50000\times10^{-12}\times100 = \underline{\underline{5\mu C}}$$
$$Q_{47} = 4\times10^{-6}\times100 = \underline{\underline{400\mu C}}$$
$$Q_T = 51.25\times10^{-6}\times100 = \underline{\underline{5.125mC}}$$

The last line in each example is a check to ensure that the total charge is the same as all the other values of charge added together.

Exercise 3.

1) A capacitor consists of two parallel plates of area $10cm \times 6.5cm$. The distance between the plates is 0.09 mm. Calculate the capacitance if ε_r=2.

2) If the supply to Q.1 is 110 V d.c. determine the energy stored in the capacitor.

3) A second capacitor of area $6.5\,\text{cm} \times 8.8\,\text{cm}$ and distance between the plates of 0.7 mm is connected in parallel with the capacitor from Q.1. Determine:
   a) the total capacitance
   b) the charge in each capacitor
   c) the total energy stored.

4) A variable capacitor of effective plate are 250 cm^2 is set so that 80 % of it is used. If the relative permittivity is 1.4, and the distance between the plates is 0.11 mm what will be the additional capacitance to be connected in parallel to improve the overall capacitance to 5 nF. If the capacitor is of the same type, what area will be in use?

4: Capacitors connected in series

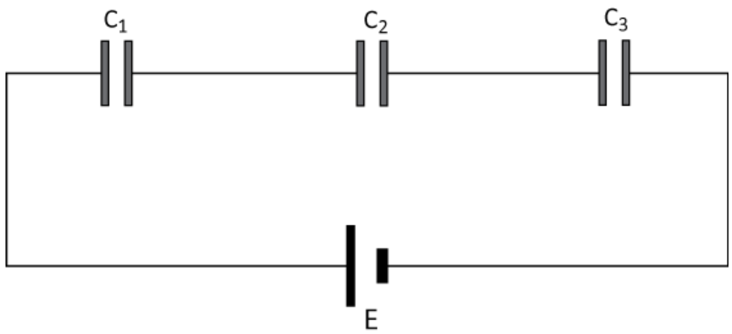
In this session the student will:

- Gain an understanding of how capacitors are connected in series.
- Gain an understanding of the effects of capacitors connected in series.

In the previous session we dealt in some detail with the effect of connecting capacitors in parallel. We saw that when capacitors are connected in parallel then their overall value increases. In effect their plate size gets bigger without the distance between the plates increasing. In this session we will consider the nature of capacitors when they are connected in series.

Capacitors connected in series

Look at the diagram below.



With capacitors connected in series, we have no increase in the area of the plate, so the capacitance won't increase, however we do have an increase in the overall distance between the plates. This increase in the distance, and hence thickness of the dielectric, will inevitably lead to a reduction in the overall capacitance.

As with resistors connected in series, the current in the circuit remains constant and the voltage is dropped across each capacitor in the circuit. The one thing that remains constant is the level of charge. Have a look at how this works out below.

$$Q_T = Q_1 = Q_2 = Q_3$$

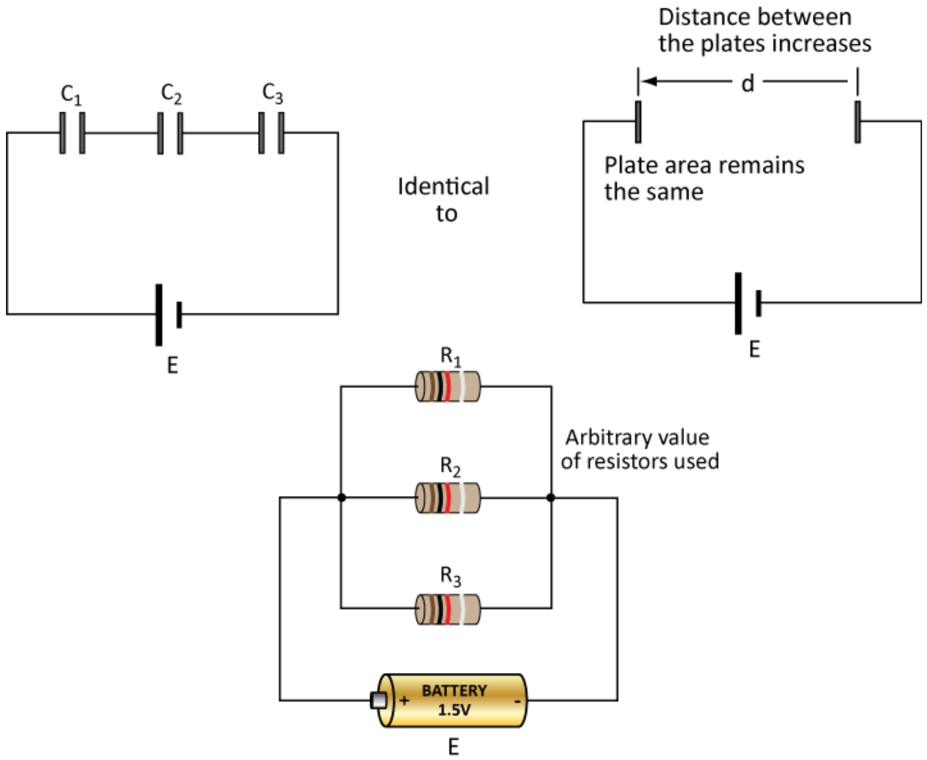
$$\text{Also } U_S = U_1 + U_2 + U_3$$

$$Q = CU \quad \text{transposing } U = \frac{Q}{C}$$

$$\text{substitute } \frac{\cancel{Q}}{C_T} = \frac{\cancel{Q}}{C_1} + \frac{\cancel{Q}}{C_2} + \frac{\cancel{Q}}{C_3}$$

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

Therefore, when we add up capacitors in series, we add up their reciprocal, just as we do for resistors in parallel.

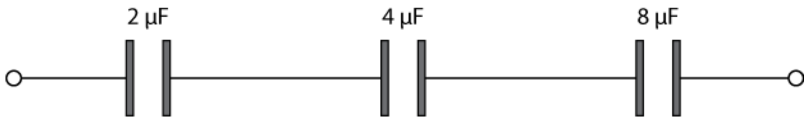


The diagram above shows the resistors connected in parallel compared to capacitors connected in series. Here the reduction in overall capacitance is due the increase in distance between the plates of the capacitor. Effectively the dielectric has been increased in width but the area of the plates has not.

With the resistors, the reduction in resistance is due to the variety of paths that the current can flow.

Let's have a look at a couple of examples.

1). Three capacitors valued at 2 μF, 4 μF and 8 μF are connected in series. Determine the total capacitance.



Notice the overall reduction in capacitance.

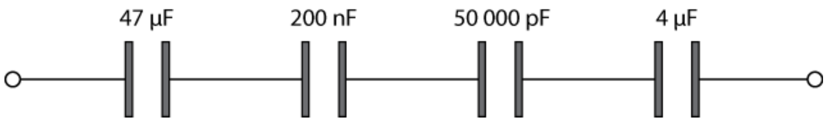
$$\frac{1}{C_T}=\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}$$

$$\frac{1}{C_T}=\frac{1}{2\times10^{-6}}+\frac{1}{4\times10^{-6}}+\frac{1}{8\times10^{-6}}$$

$$\frac{1}{C_T}=500000+250000+125000=875000$$

$$C_T=\underline{\underline{1.14\times10^{-6}}}=\underline{\underline{1.14\mu\text{F}}}$$

2). Four capacitors of values 47 μF, 200 nF, 50 000 pF and 4 μF are connected in series. What is the total value of capacitance?



$$\frac{1}{C_T}=\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}+\frac{1}{C_4}$$

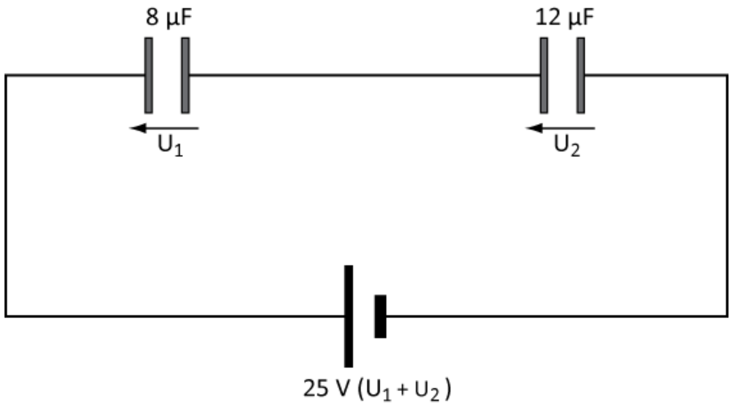
$$\frac{1}{C_T}=\frac{1}{47\times10^{-6}}+\frac{1}{200\times10^{-9}}+\frac{1}{50000\times10^{-12}}+\frac{1}{4\times10^{-6}}$$

$$\frac{1}{C_T}=21276.6+5000000+20000000+250000=25271276.6$$

$$C_T=\underline{\underline{39.57\times10^{-9}}}=\underline{\underline{39.57\text{nF}}}$$

Again, notice just how small the capacitance has become. As a rule, the total capacitance will be lower than the least value of capacitor that is connected in the series circuit.

Let's consider a series circuit with two capacitors of value 8 µF and 12 µF connected across a 25 V supply.



We already know that the total voltage is made up of the voltages dropped across each capacitor. This is the same as it would be in a series resistive circuit.

We also know with a series circuit that the charge is the same in each capacitor. You can understand this as being similar to the current flow in a series circuit being constant.

We'll look at how we can determine the voltage dropped across each capacitor.

Try to follow the working out shown below.

$$Q_T = Q_1 = Q_2$$

$$Q = C_T U_S = C_n U_n \quad \text{where } n \text{ is any number-transpose}$$

$$\frac{C_T}{C_n} = \frac{U_n}{U_S} \quad \text{transpose}$$

$$U_n = U_S \times \frac{C_T}{C_n}$$

The total charge is the same in each capacitor. We can alter the equation used in line 2 of the above working out to get line 3.

We can also work out the voltage across each capacitor by determining the total charge and then simply dividing this value by the capacitance.

$$Q = CU$$

$$U = \frac{Q_T}{C}$$

Don't let all of this maths frighten you. It is useful for you to be able to determine the voltage dropped across a capacitor when it is connected in series.

Try the examples below.

3). Two capacitors having values of 3 µF and 8 µF are connected in series. The supply voltage is 25 V. What is the voltage dropped across each capacitor?

$$\frac{1}{C_T}=\frac{1}{C_1}+\frac{1}{C_2}$$

$$\frac{1}{C_T}=\frac{1}{3\times10^{-6}}+\frac{1}{8\times10^{-6}}$$

$$\frac{1}{C_T}=333333+125000=458333$$

$$C_T=\underline{\underline{2.18\times10^{-6}}}=\underline{\underline{2.18\mu\text{F}}}$$

$$Q_T=CU$$

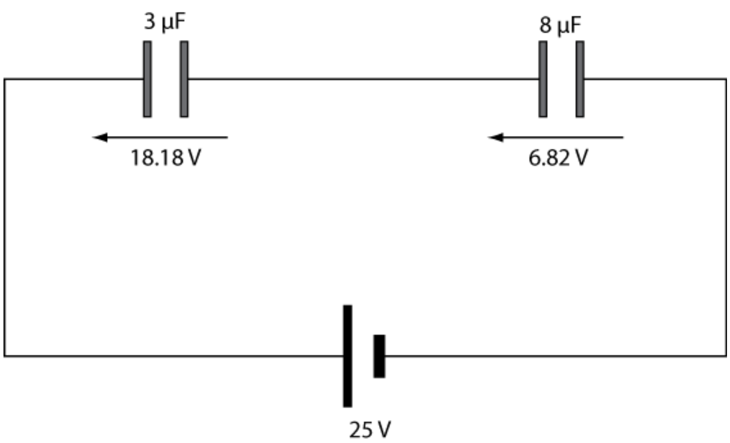
$$Q_T=2.18\times10^{-6}\times25=\underline{\underline{54.5\mu C}}$$

$$U_1=\frac{Q_T}{C_1}=\frac{54.5\times10^{-6}}{3\times10^{-6}}=\underline{\underline{18.18V}}$$

$$U_2=\frac{Q_T}{C_2}=\frac{54.5\times10^{-6}}{8\times10^{-6}}=\underline{\underline{6.82V}}$$

There are two stages with this problem. Firstly, you have to determine the total capacitance, and then you have to find the volt drop.

The larger volt drop appears across the smaller capacitor. This must be so if the level of charge is to remain the same in each capacitor. Below is a diagram with all the values filled in.



4). Three capacitors valued at 2 μF, 4 μF and 8 μF are connected in series. Determine the voltage dropped across each capacitor if the supply voltage is 100 V.

$$\frac{1}{C_T}=\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}$$

$$\frac{1}{C_T}=\frac{1}{2\times10^{-6}}+\frac{1}{4\times10^{-6}}+\frac{1}{8\times10^{-6}}$$

$$C_T=\underline{\underline{1.143\times10^{-6}}}=\underline{\underline{1.14\mu\text{F}}}$$

$$Q=CU=1.143\times10^{-6}\times100=\underline{\underline{114.3\mu C}}$$

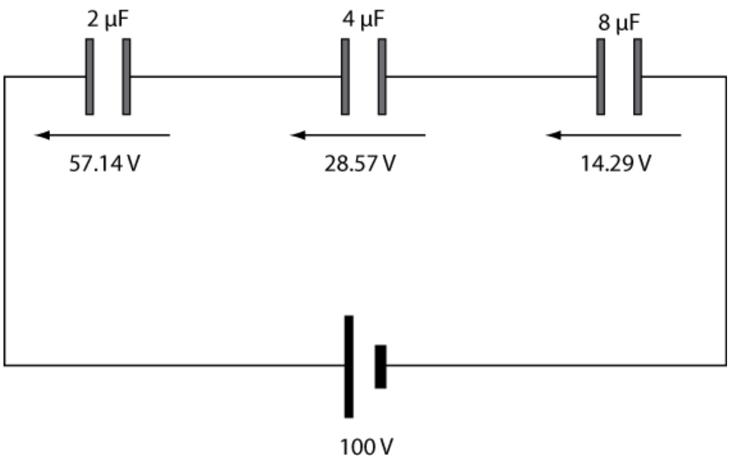
$$U_1=\frac{Q_T}{C_1}=\frac{114.3\times10^{-6}}{2\times10^{-6}}=\underline{\underline{57.14V}}$$

$$U_2=\frac{Q_T}{C_2}=\frac{114.3\times10^{-6}}{4\times10^{-6}}=\underline{\underline{28.57V}}$$

$$U_3=\frac{Q_T}{C_2}=\frac{114.3\times10^{-6}}{8\times10^{-6}}=\underline{\underline{14.29V}}$$

Again, the process is the same. You first find the total value of capacitance and then you begin to look for the voltages dropped across the individual capacitors.

Again, there is a diagram below with all the parts fully labelled so that you can refer to it as you look through the problem.



If you are still not sure, keep looking at the two examples. My working out is accurate.

You can always check your answer by seeing whether the charge across each capacitor is the same as the total charge, as well as being the same as each other.

Exercise 4.

1) What are the three ways in which the level of capacitance can be increased?

2) Three capacitors of values 47 μF, 33 μF and 15 μF are connected in parallel. What is the total capacitance? If the supply is 100 V, what will be the level of charge?

3) Three capacitors of values 47 μF; 33 μF and 15 μF are connected in series. What is the total capacitance? If the supply is 100 V, what will be the level of charge?

4) What is the voltage dropped across each capacitor in question 3?

5) Two capacitors of capacitance 25 μF and 12 μF are connected in series. What is the value of the third capacitor necessary to achieve a total capacitance of 6 μF?

6) If the voltage supplied to question 5 is 150 V d.c, what will be the voltage dropped across each capacitor?

5: Practical capacitors

In this session the student will:

- Describe the practical uses of capacitors.

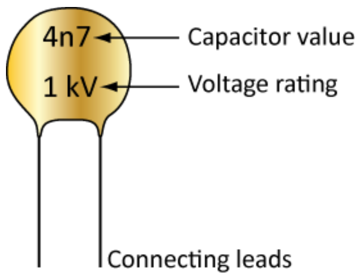
You should also be aware of the many different types of capacitors. I'll provide a list of some of them. Be aware that the name that is attached to each one describes the type of dielectric that each capacitor has. Each type of capacitor is used in specific areas, but not each type is suitable for every circumstance.

This is information that you should have already come across; however, it isn't a bad thing to be reminded of the most common types of capacitor. There are many other types as well.

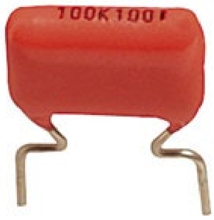
Capacitor type	Uses
Air	Used in laboratory work.
Paper	Used in power factor correction and some electronic circuits.
Plastic film	Types such as polycarbonate, polyester and polystyrene. Used in electronic circuits for filtering, coupling and bypassing.
Metallised paper	Used in automobile ignition circuits-local short circuits can self-heal!
Mica	Used in electronic tuning circuits.
Ceramic	Used in electronic circuits for signal coupling, filtering and frequency selection.
Electrolytic	Used in electronic circuits for power supplies, bypassing, coupling at low frequencies etc. They have very high capacitance values.

Ceramic disc

This type has a working voltage of up to 750 V d.c. and capacitance values of between 2.2 pF and 0.1 µF. It has excellent stability and a tolerance of ±2%, and it is used in high frequency circuits.

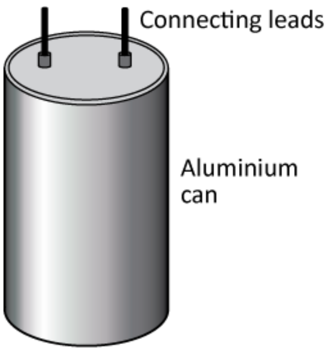


Polyester



Polystyrene

Paper

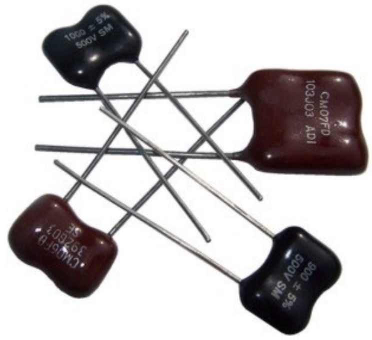


They are used in fluorescent lighting circuits, motors etc. particularly for power factor correction.

Air

Air capacitors have capacitance values ranging from 50 pF to 1 000 pF. They are used where a variety of capacitances are required such as in radios etc. The variation in capacitance values allows specific frequencies to be picked up.

Mica



This type of capacitor is expensive but very accurate, within 1% and has excellent stability. It comes in a range of capacitance values from 2 pF to 10 000 pF, and has a working voltage of up to 350 V d.c. It is used in tuned circuits and filters.

Electrolytic

Electrolytic capacitors are used where large values of capacitance are required in a small space. They usually have values ranging from 0.1 µF to 10 F! The largest types are used in computer memory retention.

Radial

Axial

Electrolytic capacitors come in a variety of shapes and sizes, but it is critical that they are connected the right way round. All electrolytic capacitors have some means of stating which end is positive and which is negative. With some it can be arrows pointing to the negative terminal, with others it can be a ridge set at the positive end. Whatever way is used it is essential that these capacitors are only used on d.c. circuits and are always connected the right way round, even when testing them!

Although electrolytic capacitors have their values printed onto them, many of the non-polarised types use colour coding similar to that used by resistors.

Working voltage

A capacitor is a device made up of two conductors called plates separated by an insulator called a dielectric. This you already know! The problem is however, that the dielectric has a voltage level at which it will break down or have a puncture. When the dielectric breaks down then the capacitor merely becomes a conductor (short circuit) or a break in the circuit (open circuit) depending on what has happened. We need therefore to limit the voltage that can be applied to the plates of the capacitor to eliminate the chance of failure.

The voltage limit that we set on capacitors is called the ***working voltage***.

The working voltage is the safe level of d.c. that can be applied to a capacitor without its dielectric breaking down.

If a puncture occurs in the dielectric, then a path has been created through which current can flow; the capacitor becomes a resistor and is assumed to have shorted out. There are some materials that self-heal such as air, oil and metallised paper, however most damaged capacitors have just to be thrown away.

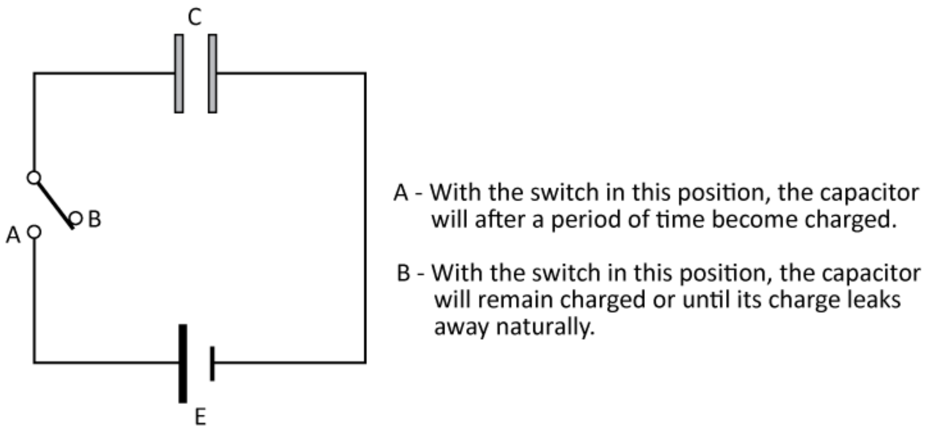
For most capacitors, it is worthwhile keeping the working voltage at a point well below the stated value. However, for electrolytic capacitors it is necessary to keep the working voltage at a point 10 %-20 % below the stated value. This is because the electrolytic capacitor relies on the working voltage to maintain the dielectric.

When connected to a.c. it is just as important to maintain the working voltage at a point below the stated value. The peak voltage must be considered not just the rms value; it is the maximum voltage that can cause the damage. Another thing to remember is not to use an electrolytic capacitor in an a.c. circuit.

The need not to use an electrolytic capacitor in an a.c. circuit is because in its manufacturing process passing current one way between the plates creates the dielectric. If a.c. is later applied to the capacitor then the process that created the dielectric is reversed and the capacitor breaks down.

Charged capacitors

Have a look below.



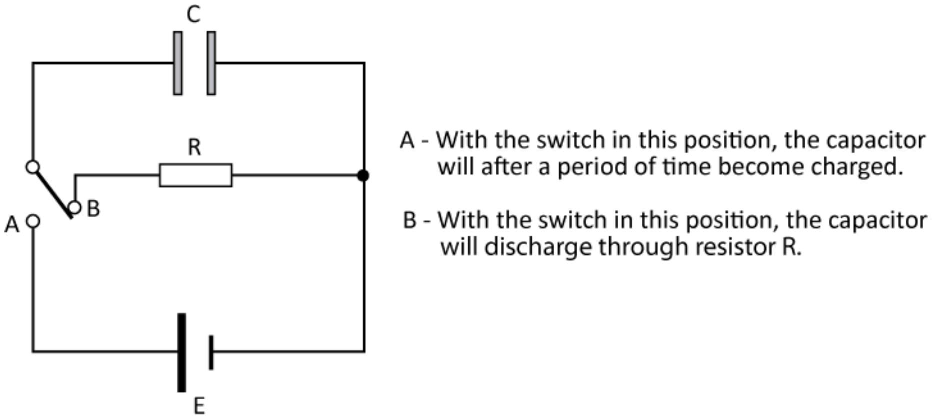
Here you can see that a capacitor has been charged up by a supply, a switch is then moved and the supply is disconnected from the capacitor; the capacitor is now fully charged and, in a perfect situation, will retain all the energy that it has stored.

Paper dielectrics are by far the worst type of capacitor for allowing this charge to '**leak**' away. Mica is the best.

If there is no means of discharging the capacitor the energy will be naturally dissipated through the next person or object that comes along. This could be dangerous and some means of limiting this effect has to be used.

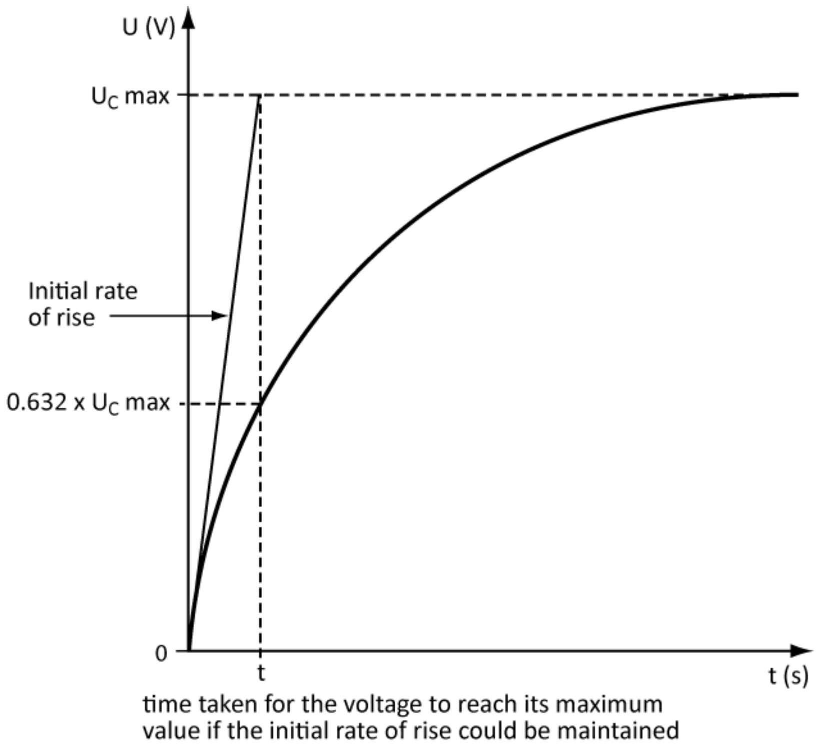
BS 7671 recognises this problem and covers this eventuality with Regulation 537.2.1.4 and Regulation 559.8.

As no figures are given in BS 7671, it is necessary to work to some other values. We'll look at how the time taken for discharging a capacitor can be determined.



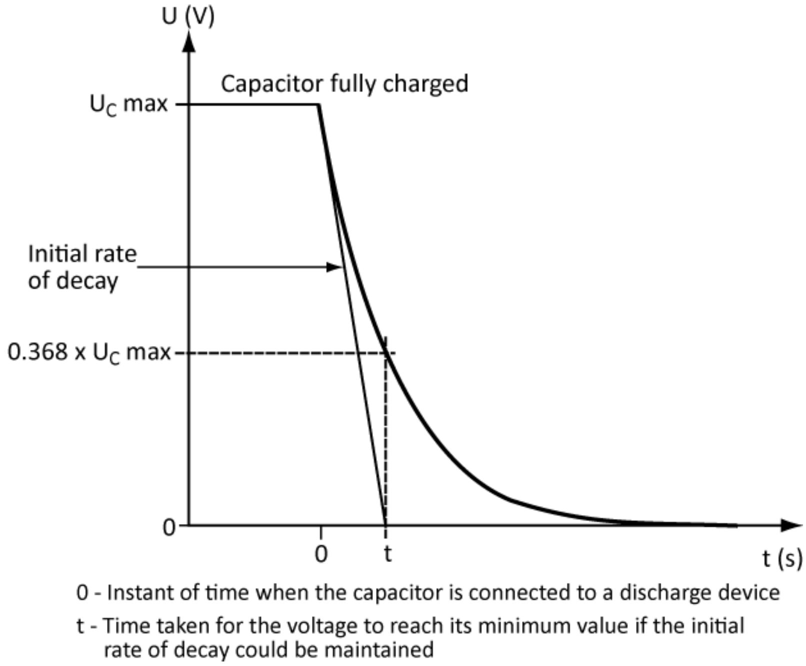
The energy in the capacitor discharges through the resistor over a period of time. The time taken for the capacitor to discharge depends on the value of the resistor.

When a capacitor charges up it doesn't just rise from zero to a maximum instantly. There is a lag in the system. This lag can be shown using a graph. Have a look below.



Notice that the time for the voltage across the capacitor to reach a maximum is not constant. It starts rising quite steeply but then falls off until after a period of time it has reached a maximum value. This is recognised as being completed after five time constants (we'll look at time constants over the next few pages).

We'll look at some of the labelling of this graph in the next few pages. As you may expect, a similar graph can be drawn for the discharging of a capacitor.



Here the current falls rapidly and then the rate of fall slows until the minimum value is reached.

As I've already stated, the rate at which the current rises or falls depends on two factors. These two factors are the capacitance and the resistance connected in series with the capacitor.

The product of the capacitance and the resistance, $C \times R$, is called the **time constant**, τ. (Greek letter-tau (toor)).

The time constant is the time taken for the voltage across a capacitor, or current through a capacitor, to rise to approximately 63 % of its final maximum value, or fall to approximately 37 % of its final minimum value. We'll look at a couple of examples.

1). A 20 µF capacitor is discharged through a 100 kΩ resistor. What is the time constant of the circuit?

$$\tau = CR$$
$$\tau = 20 \times 10^{-6} \times 100 \times 10^{3}$$
$$\tau = \underline{\underline{2\text{s}}}$$

Note that this is the time taken for the current or voltage to fall to 63% of its final value. The 63% is used because that is always the percentage of the maximum to reach the first time constant.

The final value, whether a maximum or a minimum, is said to occur after five time constants. Therefore, in our example it takes 10 seconds for the voltage to fall to zero.

In most circuits where capacitors are used, such as fluorescent fittings, power factor correction capacitors etc. there are resistors connected across the terminals of the capacitor.

These resistors allow the capacitor to discharge safely over a short period of time. Alter the resistor value and you will alter the time taken to charge or discharge. It is common to find resistance values of about 200 kΩ.

Try one more example.

2). A power factor correction capacitor rated at 8.7 µF is discharged through a 200 kΩ resistor. How long will it take the capacitor to fully discharge?

$$\tau = CR$$
$$\tau = 8.7 \times 10^{-6} \times 200 \times 10^{3}$$
$$\tau = \underline{\underline{1.74\text{s}}}$$
$$5 \text{ time constants} = 5 \times 1.74 = \underline{\underline{8.7\text{s}}}$$

Again, in this example, it takes 1.74 s to reach 63 % of its final value, one time constant. It also takes 8.7 s to reach its final value, or 100 % (near enough) of its final value.

There is just one more small area that we have to consider, and that is static electricity.

We have already looked at how charge can be separated and at how this separation of charge can be used in capacitors. The classic example of charge separation is the rubbing of a balloon on the jumper and it then ‘sticking’ to the wall. There has been charge separation.

When you walk across a nylon carpet and then touch something metal, you may well find that you receive an electric shock. This electric shock has been caused by the charge that you have built up suddenly discharging through you when you touch something that conducts. This shock can have quite a high voltage, and can be dangerous to certain electronic circuits, particularly circuits containing chips.

Before you work on any circuitry, you should always discharge yourself to some earthed metalwork or wear a discharge band on your wrist to make sure that you are at a low potential (voltage) relative to the circuitry.

Capacitance however appears in many areas, without a capacitor being present. As long as there are two conductors separated by an insulator, then there will be a capacitive effect.

We have already looked at an example where we looked at a length of MI cable. After they have been tested, a length of MI often retains sufficient charge to give a shock. Cables that run parallel for long distances, such as transmission lines, gain a certain level of capacitance. There is even a capacitive effect between the windings of coils, although it is very small and is swamped by the size of the inductor, it is still there.

Exercise 5.

1) Why are discharge resistors connected across large industrial capacitors?

2) State three examples of capacitors used in an industrial setting.

3) How can an electronic circuit be protected from static electricity?

4) What regulation covers the discharge of capacitive energy?

5) If a capacitor has a value of 2 μF and is charged up to 230 V, what will be the value of discharge resistor needed to reduce the voltage to a minimum within a time of 30 s?

6) Explain working voltage.

Formulae

Here are the formulae that you have used in this unit.

Capacitors in parallel	$C_T = C_1 + C_2 + C_3$
Capacitors in series	$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$
Electric field strength	$E = \frac{U}{d}$
Electric flux density	$D = \frac{Q}{A}$
Absolute permittivity	$\varepsilon = \frac{D}{E}$
	$\varepsilon = \varepsilon_0 \varepsilon_r$
Capacitance	$C = \frac{\varepsilon A}{d} = \frac{\varepsilon_0 \varepsilon_r A}{d}$
Charge	$Q = CU$
Energy	$E = \frac{1}{2} C U^2$

Now try the end test over the page. You should make sure that you gain in excess of 85% of the marks available. Any less and you should attempt the unit again!

B&B Training Associates

Engineering Learning Materials

Attempt all questions.

All marks are shown in the right-hand margin.

You should aim to pass with an 85 % minimum mark.

Anything less than this mark should lead you to re-read the text.

1) State the similarities and differences when comparing resistors connected in series and parallel with capacitors connected in series and parallel. 4
2) Show what happens when a positive and negative charge come into close proximity with each other. 3
3) Draw and label the lines of electric flux between two plates. 2
4) Draw a fully labelled capacitor. 2
5) State the unit and symbol of electric flux. 2
6) What is the relationship between electric flux and electric flux density? 3
7) Calculate the charge stored in a capacitor if the electric flux density is $0.4\,{}^{mC}\!/_{m^2}$ and the area of each plate is 750 cm^2. 4
8) Define the term electric field strength. State its units and its symbol. 3
9) What does the force on an electric charge depend on? 2
10) A capacitor has a supply of 400 V connected across it. The thickness of the dielectric is 0.25 mm. What is the electric field strength? 5
11) Define permittivity. What is its unit and symbol? 3
12) The area of the plates of a capacitor are 1 000 cm^2. The thickness of the dielectric is 0.25 mm. Assuming that the supply is 250 V and the relative permittivity is 5, determine the following the:
    a) capacitance 4
    b) charge stored in the capacitor 2
    c) electric field strength. 2
13) Three capacitors valued at 2.5 µF, 7 µF and 8 µF are connected in parallel. Determine the total capacitance. 4
14) Four capacitors of values 47 µF, 200 nF, 50 000 pF and 4 µF are connected in series. What is the total value of capacitance? 2

15) Three capacitors valued at 2 μF, 4 μF and 8 μF are connected in series. Determine the voltage dropped across each capacitor if the supply voltage is 100V. 6

16) State why the term ‘working voltage’ is used. 2

17) Why must an electrolytic capacitor only be connected one way? 2

18) An 8.7 μF capacitor has a voltage of 230 V d.c. Calculate the amount of energy stored in the capacitor. 3

Total marks 60