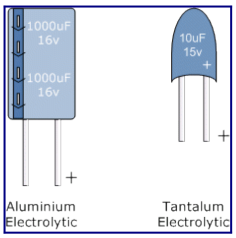
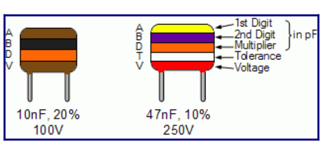
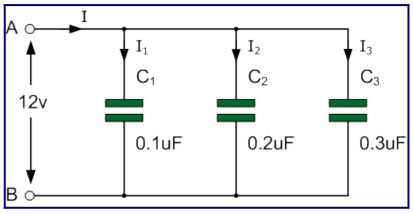
https://www.electronics-tutorials.ws/category/capacitor

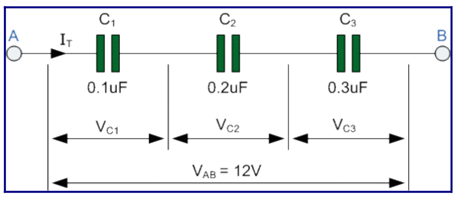
Capacitors (11)

	**Introduction to Capacitors** The capacitor is a component which has the ability or "capacity" to store energy in the form of an electrical charge producing a potential difference (Static Voltage) across its plates, much like a small rechargeable battery. There are many different kinds of capacitors availabl…
	**Types of Capacitor** The types of capacitors available range from very small delicate trimming capacitors using in oscillator or radio circuits, up to large power metal-can type capacitors used in high voltage power correction and smoothing circuits. The comparisons between the different types o...
	**Capacitor Characteristics** There are a bewildering array of capacitor characteristics and specifications associated with the humble capacitor and reading the information printed onto the body of a capacitor can sometimes be difficult to understand especially when colours or numeric codes are used. Each fa...
$Q = C \times V$	**Capacitance and Charge** Capacitors consist of two parallel conductive plates (usually a metal) which are prevented from touching each other (separated) by an insulating material called the "dielectric". When a voltage is applied to these plates an electrical current flows charging up one plate with a po...
	**Capacitor Colour Codes** However, when the value of the capacitance is of a decimal value problems arise with the marking of the "Decimal Point" as it could easily not be noticed resulting in a misreading of the actual capacitance value. Instead letters such as p (pico) or n (nano) are used in place of t...



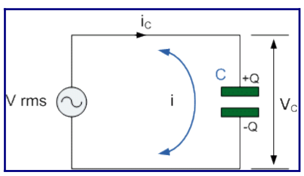
Capacitors in Parallel

The voltage (Vc) connected across all the capacitors that are connected in parallel is THE SAME. Then, Capacitors in Parallel have a "common voltage" supply across them giving: VC1 = VC2 = VC3 = VAB = 12V In the following circuit the capacitors, C1, C2 and C3 ...



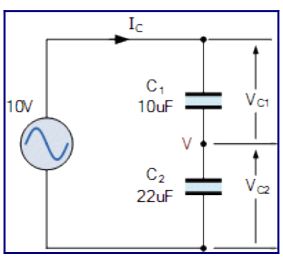
Capacitors in Series

For series connected capacitors, the charging current (iC) flowing through the capacitors is THE SAME for all capacitors as it only has one path to follow. Then, Capacitors in Series all have the same current flowing through them as iT = i1 = i2&n...



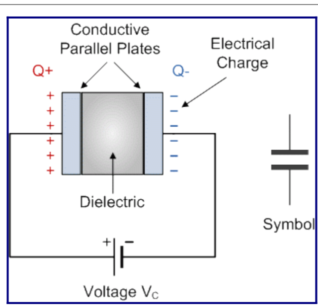
Capacitance in AC Circuits

When capacitors are connected across a direct current DC supply voltage, their plates charge-up until the voltage value across the capacitor is equal to that of the externally applied voltage. The capacitor will hold this charge indefinitely, acting like a temporary storage devic...



Capacitive Voltage Divider

But just like resistive circuits, a capacitive voltage divider network is not affected by changes in the supply frequency even though they use capacitors, which are reactive elements, as each capacitor in the series chain is affected equally by changes in supply frequency. But b...



Capacitor Tutorial Summary

Capacitors are energy storage devices which have the ability to store an electrical charge across its plates. Thus capacitors store energy as a result of their ability to store charge and an ideal capacitor would not loose its stored energy. The simplest construction of a capaci...

Ultracapacitors

Unlike the resistor, which dissipates energy in the form of heat, the ideal capacitor does not loose its energy. We have also seen that the simplest form of a capacitor is two parallel conducting metal plates which are separated by an insulating material, such as air, mica, paper...

https://www.electronics-tutorials.ws/capacitor/cap_1.html

Introduction to Capacitors

Capacitors are simple passive device that can store an electrical charge on their plates when connected to a voltage source.

The capacitor is a component which has the ability or “capacity” to store energy in the form of an electrical charge producing a potential difference (*Static Voltage*) across its plates, much like a small rechargeable battery.

There are many different kinds of capacitors available from very small capacitor beads used in resonance circuits to large power factor correction capacitors, but they all do the same thing, they store charge.

In its basic form, a capacitor consists of two or more parallel conductive (metal) plates which are not connected or touching each other, but are electrically separated either by air or by some form of a good insulating material such as waxed paper, mica, ceramic, plastic or some form of a liquid gel as used in electrolytic capacitors. The insulating layer between a capacitors plates is commonly called the **Dielectric**.

Due to this insulating layer, DC current can not flow through the capacitor as it blocks it allowing instead a voltage to be present across the plates in the form of an electrical charge.

The conductive metal plates of a capacitor can be either square, circular or rectangular, or they can be of a cylindrical or spherical shape with the general shape, size and construction of a parallel plate capacitor depending on its application and voltage rating.

When used in a direct current or DC circuit, a capacitor charges up to its supply voltage but blocks the flow of current through it because the dielectric of a capacitor is non-conductive and basically an insulator. However, when a capacitor is connected to an alternating current or AC circuit, the flow of the current appears to pass straight through the capacitor with little or no resistance.

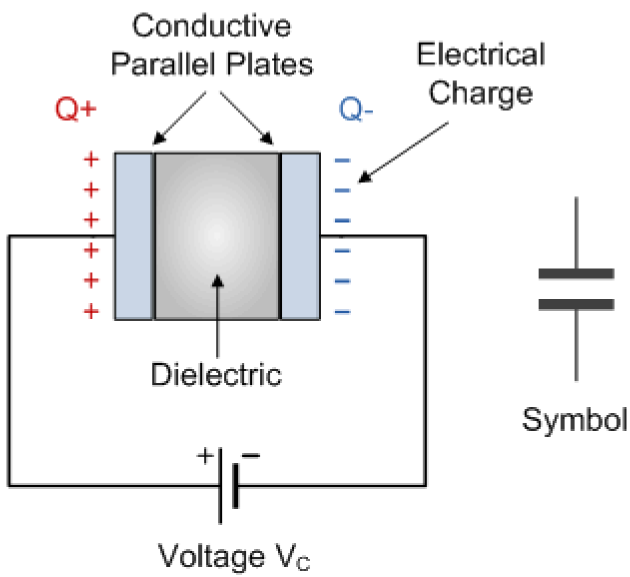
There are two types of electrical charge, a positive charge in the form of Protons and a negative charge in the form of Electrons. When a DC voltage is placed across a capacitor, the positive (+ve) charge quickly accumulates on one plate while a corresponding and opposite negative (-ve) charge accumulates on the other plate. For every particle of +ve charge that arrives at one plate a charge of the same sign will depart from the -ve plate.

Then the plates remain charge neutral and a potential difference due to this charge is established between the two plates. Once the capacitor reaches its steady state condition an electrical current is unable to flow through the capacitor itself and around the circuit due to the insulating properties of the dielectric used to separate the plates.

The flow of electrons onto the plates is known as the capacitors **Charging Current** which continues to flow until the voltage across both plates (and hence the capacitor) is equal to the applied voltage Vc. At this point the capacitor is said to be “fully charged” with electrons.

The strength or rate of this charging current is at its maximum value when the plates are fully discharged (initial condition) and slowly reduces in value to zero as the plates charge up to a potential difference across the capacitors plates equal to the source voltage.

The amount of potential difference present across the capacitor depends upon how much charge was deposited onto the plates by the work being done by the source voltage and also by how much capacitance the capacitor has and this is illustrated below.



The parallel plate capacitor is the simplest form of capacitor. It can be constructed using two metal or metallised foil plates at a distance parallel to each other, with its capacitance value in Farads, being fixed by the surface area of the conductive plates and the distance of separation between them. Altering any two of these values alters the value of its capacitance and this forms the basis of operation of the variable capacitors.

Also, because capacitors store the energy of the electrons in the form of an electrical charge on the plates the larger the plates and/or smaller their separation the greater will be the charge that the capacitor holds for any given voltage across its plates. In other words, larger plates, smaller distance, more capacitance.

By applying a voltage to a capacitor and measuring the charge on the plates, the ratio of the charge Q to the voltage V will give the capacitance value of the capacitor and is therefore given as: $C = Q/V$ this equation can also be re-arranged to give the familiar formula for the quantity of charge on the plates as: $Q = C \times V$

Although we have said that the charge is stored on the plates of a capacitor, it is more exact to say that the energy within the charge is stored in an “electrostatic field” between the two plates. When an electric current flows into the capacitor, it charges up, so the electrostatic field becomes much stronger as it stores more energy between the plates.

Likewise, as the current flowing out of the capacitor, discharging it, the potential difference between the two plates decreases and the electrostatic field decreases as the energy moves out of the plates.

The property of a capacitor to store charge on its plates in the form of an electrostatic field is called the **Capacitance** of the capacitor. Not only that, but capacitance is also the property of a capacitor which resists the change of voltage across it.

The Capacitance of a Capacitor

Capacitance is the electrical property of a capacitor and is the measure of a capacitors ability to store an electrical charge onto its two plates with the unit of capacitance being the **Farad** (abbreviated to F) named after the British physicist Michael Faraday.

Capacitance is defined as being that a capacitor has the capacitance of **One Farad** when a charge of **One Coulomb** is stored on the plates by a voltage of **One volt**. Note that capacitance, C is always positive in value and has no negative units. However, the Farad is a very large unit of measurement to use on its own so sub-multiples of the Farad are generally used such as micro-farads, nano-farads and pico-farads, for example.

Standard Units of Capacitance

- Microfarad(μF)1μF = 1/1,000,000 = 0.000001 = 10^{-6} F
- Nanofarad(nF)1nF = 1/1,000,000,000 = 0.000000001 = 10^{-9} F
- Picofarad(pF)1pF = 1/1,000,000,000,000 = 0.000000000001 = 10^{-12} F

Then using the information above we can construct a simple table to help us convert between pico-Farad (pF), to nano-Farad (nF), to micro-Farad (μF) and to Farads (F) as shown.

Pico-Farad (pF)	Nano-Farad (nF)	Micro-Farad (μF)	Farads (F)
1,000	1.0	0.001	
10,000	10.0	0.01	
1,000,000	1,000	1.0	
	10,000	10.0	
	100,000	100	
	1,000,000	1,000	0.001
		10,000	0.01
		100,000	0.1
		1,000,000	1.0

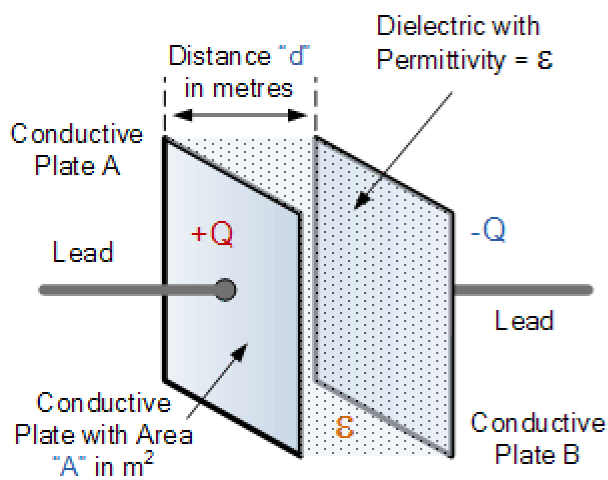
Capacitance of a Parallel Plate Capacitor

The capacitance of a parallel plate capacitor is proportional to the area, A in metres^2 of the smallest of the two plates and inversely proportional to the distance or separation, d (i.e. the dielectric thickness) given in metres between these two conductive plates.

The generalised equation for the capacitance of a parallel plate capacitor is given as: $C=\varepsilon(A/d)$ where ε represents the absolute permittivity of the dielectric material being used. The dielectric constant, ε_o also known as the "permittivity of free space" has the value of the constant $8.854\text{x}10^{-12}$ Farads per metre.

To make the maths a little easier, this dielectric constant of free space, ε_o, which can be written as: $1/(4\pi\text{x}9\times10^9)$, may also have the units of picofarads (pF) per metre as the constant giving: 8.85 for the value of free space. Note though that the resulting capacitance value will be in picofarads and not in farads.

Generally, the conductive plates of a capacitor are separated by some kind of insulating material or gel rather than a perfect vacuum. When calculating the capacitance of a capacitor, we can consider the permittivity of air, and especially of dry air, as being the same value as a vacuum as they are very close.



Capacitance Example No1

A capacitor is constructed from two conductive metal plates 30cm x 50cm which are spaced 6mm apart from each other, and uses dry air as its only dielectric material. Calculate the capacitance of the capacitor.

$$\text{Using:} \quad C = \varepsilon_o \frac{A}{d}$$

$$\text{where:} \ \varepsilon_o = 8.854 \times 10^{-12}$$

$$A = 0.3 \times 0.5\, m^2 \quad \text{and} \quad d = 6 \times 10^{-3}\, m$$

$$C = \frac{8.854 \times 10^{-12} \times (0.3 \times 0.5)}{6 \times 10^{-3}} = 0.221nF$$

Then the value of the capacitor consisting of two plates separated by air is calculated as 0.221nF, or 221pF.

The Dielectric of a Capacitor

As well as the overall size of the conductive plates and their distance or spacing apart from each other, another factor which affects the overall capacitance of the device is the type of dielectric material being used. In other words the “Permittivity” (ε) of the dielectric.

The conductive plates of a capacitor are generally made of a metal foil or a metal film allowing for the flow of electrons and charge, but the dielectric material used is always an insulator. The various insulating materials used as the dielectric in a capacitor differ in their ability to block or pass an electrical charge.

This dielectric material can be made from a number of insulating materials or combinations of these materials with the most common types used being: air, paper, polyester, polypropylene, Mylar, ceramic, glass, oil, or a variety of other materials.

The factor by which the dielectric material, or insulator, increases the capacitance of the capacitor compared to air is known as the **Dielectric Constant**, **k** and a dielectric material with a high dielectric constant is a better insulator than a dielectric material with a lower dielectric constant. Dielectric constant is a dimensionless quantity since it is relative to free space.

The actual permittivity or “complex permittivity” of the dielectric material between the plates is then the product of the permittivity of free space (ε_o) and the relative permittivity (ε_r) of the material being used as the dielectric and is given as:

Complex Permittivity

$$\varepsilon = \varepsilon_o \times \varepsilon_r$$

In other words, if we take the permittivity of free space, ε_o as our base level and make it equal to one, when the vacuum of free space is replaced by some other type of insulating material, their permittivity of its dielectric is referenced to the base dielectric of free space giving a multiplication factor known as "relative permittivity", ε_r. So the value of the complex permittivity, ε will always be equal to the relative permittivity times one.

Typical units of dielectric permittivity, ε or dielectric constant for common materials are: Pure Vacuum = 1.0000, Air = 1.0006, Paper = 2.5 to 3.5, Glass = 3 to 10, Mica = 5 to 7, Wood = 3 to 8 and Metal Oxide Powders = 6 to 20 etc. This then gives us a final equation for the capacitance of a capacitor as:

$$\text{Capacitance, } C = \frac{\varepsilon_o \varepsilon_r A}{d} \text{ Farads}$$

One method used to increase the overall capacitance of a capacitor while keeping its size small is to "interleave" more plates together within a single capacitor body. Instead of just one set of parallel plates, a capacitor can have many individual plates connected together thereby increasing the surface area, A of the plates.

For a standard parallel plate capacitor as shown above, the capacitor has two plates, labelled A and B. Therefore as the number of capacitor plates is two, we can say that n=2, where "n" represents the number of plates.

Then our equation above for a single parallel plate capacitor should really be:

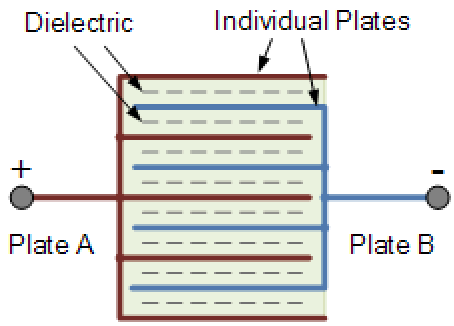
$$\text{Capacitance, } C = \frac{\varepsilon_o \varepsilon_r (n-1) A}{d} \text{ Farads}$$

However, the capacitor may have two parallel plates but only one side of each plate is in contact with the dielectric in the middle as the other side of each plate forms the outside of the capacitor. If we take the two halves of the plates and join them together we effectively only have "one" whole plate in contact with the dielectric.

As for a single parallel plate capacitor, n–1=2–1 which equals 1 as $C=(\varepsilon_o*\varepsilon_r \text{ x } 1 \text{ x } A)/d$ is exactly the same as saying: $C=(\varepsilon_o*\varepsilon_r*A)/d$ which is the standard equation above.

Now suppose we have a capacitor made up of 9 interleaved plates, then n = 9 as shown.

Multi-plate Capacitor



Now we have five plates connected to one lead (A) and four plates to the other lead (B). Then BOTH sides of the four plates connected to lead B are in contact with the dielectric, whereas only one side of each of the outer plates connected to A is in contact with the dielectric. Then as above, the useful surface area of each set of plates is only eight and its capacitance is therefore given as:

$$C = \frac{\varepsilon_0 \varepsilon_r (n-1) A}{d} = \frac{\varepsilon_0 \varepsilon_r (9-1) A}{d} = \frac{\varepsilon_0 \varepsilon_r 8A}{d}$$

Modern capacitors can be classified according to the characteristics and properties of their insulating dielectric:

- Low Loss, High Stability such as Mica, Low-K Ceramic, Polystyrene.
- Medium Loss, Medium Stability such as Paper, Plastic Film, High-K Ceramic.
- Polarized Capacitors such as Electrolytic's, Tantalum's.

Voltage Rating of a Capacitor

All capacitors have a maximum voltage rating and when selecting a capacitor consideration must be given to the amount of voltage to be applied across the capacitor. The maximum amount of voltage that can be applied to the capacitor without damage to its dielectric material is generally given in the data sheets as: WV, (working voltage) or as WV DC, (DC working voltage).

If the voltage applied across the capacitor becomes too great, the dielectric will break down (known as electrical breakdown) and arcing will occur between the capacitor plates resulting in a short-circuit. The working voltage of the capacitor depends on the type of dielectric material being used and its thickness.

The DC working voltage of a capacitor is just that, the maximum DC voltage and NOT the maximum AC voltage as a capacitor with a DC voltage rating of 100 volts DC cannot be safely subjected to an alternating voltage of 100 volts. Since an alternating voltage that has an RMS value of 100 volts will have a peak value of over 141 volts! (√2x100).

Then a capacitor which is required to operate at 100 volts AC should have a working voltage of at least 200 volts. In practice, a capacitor should be selected so that its working voltage either DC or AC should be at least 50 percent greater than the highest effective voltage to be applied to it.

Another factor which affects the operation of a capacitor is **Dielectric Leakage**. Dielectric leakage occurs in a capacitor as the result of an unwanted leakage current which flows through the dielectric material.

Generally, it is assumed that the resistance of the dielectric is extremely high and a good insulator blocking the flow of DC current through the capacitor (as in a perfect capacitor) from one plate to the other.

However, if the dielectric material becomes damaged due excessive voltage or over temperature, the leakage current through the dielectric will become extremely high resulting in a rapid loss of charge on the plates and an overheating of the capacitor eventually resulting in premature failure of the capacitor. Then never use a capacitor in a circuit with higher voltages than the capacitor is rated for otherwise it may become hot and explode.

Introduction to Capacitors Summary

We have seen in this tutorial that the job of a capacitor is to store electrical charge onto its plates. The amount of electrical charge that a capacitor can store on its plates is known as its **Capacitance** value and depends upon three main factors.

- Surface Area–the surface area, A of the two conductive plates which make up the capacitor, the larger the area the greater the capacitance.
- Distance–the distance, d between the two plates, the smaller the distance the greater the capacitance.
- Dielectric Material–the type of material which separates the two plates called the “dielectric”, the higher the permittivity of the dielectric the greater the capacitance.

We have also seen that a capacitor consists of metal plates that do not touch each other but are separated by a material called a dielectric. The dielectric of a capacitor can be air, or even a vacuum but is generally a non-conducting insulating material, such as waxed paper, glass, mica different types of plastics etc. The dielectric provides the following advantages:

- The dielectric constant is the property of the dielectric material and varies from one material to another increasing the capacitance by a factor of k.
- The dielectric provides mechanical support between the two plates allowing the plates to be closer together without touching.
- Permittivity of the dielectric increases the capacitance.
- The dielectric increases the maximum operating voltage compared to air.

Capacitors can be used in many different applications and circuits such as blocking DC current while passing audio signals, pulses, or alternating current, or other time varying wave forms. This ability to block DC currents enables capacitors to be used to smooth the output voltages of power supplies, to remove unwanted spikes from signals that would otherwise tend to cause damage or false triggering of semiconductors or digital components.

Capacitors can also be used to adjust the frequency response of an audio circuit, or to couple together separate amplifier stages that must be protected from the transmission of DC current.

When used on DC supplies a capacitor has infinite impedance (open-circuit), at very high frequencies a capacitor has zero impedance (short-circuit). All capacitors have a maximum working DC voltage rating, (WVDC) so it is advisable to select a capacitor with a voltage rating at least 50% more than the supply voltage.

There are a large variety of capacitor styles and types, each one having its own particular advantage, disadvantage and characteristics. To include all types would make this tutorial section very large so in the next tutorial about The Introduction to Capacitors I shall limit them to the most commonly used types.

https://www.electronics-tutorials.ws/capacitor/cap_2.html

Types of Capacitor

There is a large variety of different types of capacitor available in the market place and each one has its own set of characteristics and applications.

The types of capacitors available range from very small delicate trimming capacitors using in oscillator or radio circuits, up to large power metal-can type capacitors used in high voltage power correction and smoothing circuits.

The comparisons between the different *types of capacitor* is generally made with regards to the dielectric used between the plates. Like resistors, there are also variable types of capacitors which allow us to vary their capacitance value for use in radio or “frequency tuning” type circuits.

Commercial types of capacitors are made from metallic foil interlaced with thin sheets of either paraffin-impregnated paper or Mylar as the dielectric material. Some capacitors look like tubes, this is because the metal foil plates are rolled up into a cylinder to form a small package with the insulating dielectric material sandwiched in between them.

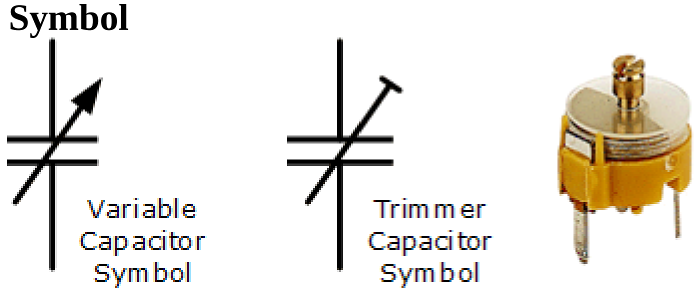
Small capacitors are often constructed from ceramic materials and then dipped into an epoxy resin to seal them. Either way, capacitors play an important part in electronic circuits so here are a few of the more “common” types of capacitor available.

Dielectric Capacitor

Dielectric Capacitors are usually of the variable type were a continuous variation of capacitance is required for tuning transmitters, receivers and transistor radios. Variable dielectric capacitors are multi-plate air-spaced types that have a set of fixed plates (the stator vanes) and a set of movable plates (the rotor vanes) which move in between the fixed plates.

The position of the moving plates with respect to the fixed plates determines the overall capacitance value. The capacitance is generally at maximum when the two sets of plates are fully meshed together. High voltage type tuning capacitors have relatively large spacings or air-gaps between the plates with breakdown voltages reaching many thousands of volts.

Variable Capacitor Symbol



As well as the continuously variable types, preset type variable capacitors are also available called **Trimmers**. These are generally small devices that can be adjusted or “pre-set” to a particular capacitance value with the aid of a small screwdriver and are available in very small capacitance's of 500pF or less and are non-polarized.

Film Capacitor Type

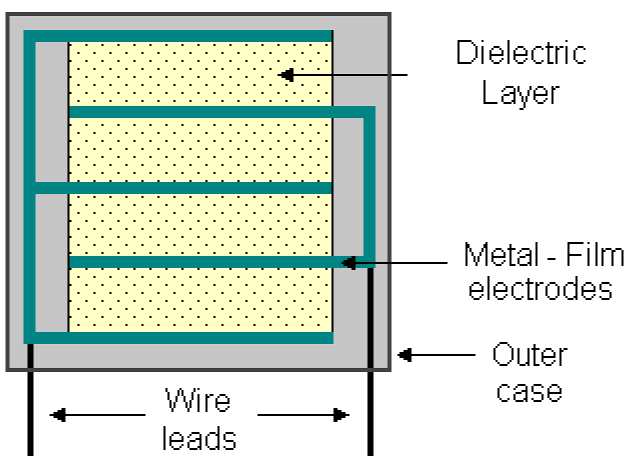
Film Capacitors are the most commonly available of all types of capacitors, consisting of a relatively large family of capacitors with the difference being in their dielectric properties. These include polyester (Mylar), polystyrene, polypropylene, polycarbonate, metalised paper, Teflon etc. Film type capacitors are available in capacitance ranges from as small as 5pF to as large as 100uF depending upon the actual type of capacitor and its voltage rating. Film capacitors also come in an assortment of shapes and case styles which include:

- Wrap & Fill (Oval & Round)–where the capacitor is wrapped in a tight plastic tape and have the ends filled with epoxy to seal them.
- Epoxy Case (Rectangular & Round)–where the capacitor is encased in a moulded plastic shell which is then filled with epoxy.
- Metal Hermetically Sealed (Rectangular & Round)–where the capacitor is encased in a metal tube or can and again sealed with epoxy.

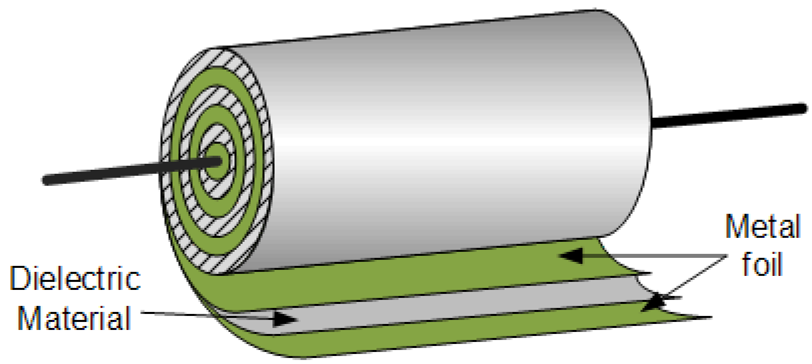
with all the above case styles available in both Axial and Radial Leads.

Film Capacitors which use polystyrene, polycarbonate or Teflon as their dielectrics are sometimes called "Plastic capacitors". The construction of plastic film capacitors is similar to that for paper film capacitors but use a plastic film instead of paper. The main advantage of plastic film capacitors compared to impregnated-paper types is that they operate well under conditions of high temperature, have smaller tolerances, a very long service life and high reliability. Examples of film capacitors are the rectangular metalised film and cylindrical film & foil types as shown below.

Radial Lead Type



Axial Lead Type



The film and foil types of capacitors are made from long thin strips of thin metal foil with the dielectric material sandwiched together which are wound into a tight roll and then sealed in paper or metal tubes.


Film Capacitor

These film types require a much thicker dielectric film to reduce the risk of tears or punctures in the film, and is therefore more suited to lower capacitance values and larger case sizes.

Metalised foil capacitors have the conductive film metalised sprayed directly onto each side of the dielectric which gives the capacitor self-healing properties and can therefore use much thinner dielectric films. This allows for higher capacitance values and smaller case sizes for a given capacitance. Film and foil capacitors are generally used for higher power and more precise applications.

Ceramic Capacitors

Ceramic Capacitors or **Disc Capacitors** as they are generally called, are made by coating two sides of a small porcelain or ceramic disc with silver and are then stacked together to make a capacitor. For very low capacitance values a single ceramic disc of about 3-6mm is used. Ceramic capacitors have a high dielectric constant (High-K) and are available so that relatively high capacitance's can be obtained in a small physical size.

They exhibit large non-linear changes in capacitance against temperature and as a result are used as de-coupling or by-pass capacitors as they are also non-polarized devices. Ceramic capacitors have values ranging from a few picofarads to one or two microfarads, (μF) but their voltage ratings are generally quite low.

Ceramic Capacitor

Ceramic types of capacitors generally have a 3-digit code printed onto their body to identify their capacitance value in pico-farads. Generally the first two digits indicate the capacitors value and the third digit indicates the number of zero's to be added. For example, a ceramic disc capacitor with the markings 103 would indicate 10 and 3 zero's in pico-farads which is equivalent to 10,000 pF or 10nF.

Likewise, the digits 104 would indicate 10 and 4 zero's in pico-farads which is equivalent to 100,000 pF or 100nF and so on. So on the image of the ceramic capacitor above the numbers 154 indicate 15 and 4 zero's in pico-farads which is equivalent to 150,000 pF or 150nF or 0.15μF. Letter codes are sometimes used to indicate their tolerance value such as: J = 5%, K = 10% or M = 20% etc.

Electrolytic Capacitors

Electrolytic Capacitors are generally used when very large capacitance values are required. Here instead of using a very thin metallic film layer for one of the electrodes, a semi-liquid electrolyte solution in the form of a jelly or paste is used which serves as the second electrode (usually the cathode).

The dielectric is a very thin layer of oxide which is grown electro-chemically in production with the thickness of the film being less than ten microns. This insulating layer is so thin that it is possible to make capacitors with a large value of capacitance for a small physical size as the distance between the plates, d is very small.

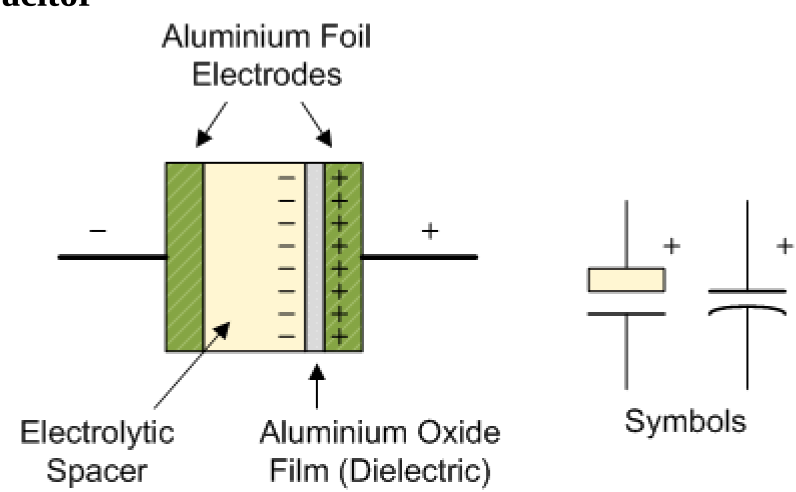
The majority of electrolytic types of capacitors are **Polarised**, that is the DC voltage applied to the capacitor terminals must be of the correct polarity, i.e. positive to the positive terminal and negative to the negative terminal as an incorrect polarisation will break down the insulating oxide layer and permanent damage may result.

Electrolytic Capacitor

All polarised electrolytic capacitors have their polarity clearly marked with a negative sign to indicate the negative terminal and this polarity must be followed.

Electrolytic Capacitors are generally used in DC power supply circuits due to their large capacitance's and small size to help reduce the ripple voltage or for coupling and decoupling applications. One main disadvantage of electrolytic capacitors is their relatively low voltage rating and due to the polarisation of electrolytic capacitors, it follows then that they must not be used on AC supplies. Electrolytic's generally come in two basic forms; **Aluminium Electrolytic Capacitors** and **Tantalum Electrolytic Capacitors**.

Electrolytic Capacitor



1.Aluminium Electrolytic Capacitors

There are basically two types of **Aluminium Electrolytic Capacitor**, the plain foil type and the etched foil type. The thickness of the aluminium oxide film and high breakdown voltage give these capacitors very high capacitance values for their size.

The foil plates of the capacitor are anodized with a DC current. This anodizing process sets up the polarity of the plate material and determines which side of the plate is positive and which side is negative.

The etched foil type differs from the plain foil type in that the aluminium oxide on the anode and cathode foils has been chemically etched to increase its surface area and permittivity. This gives a smaller sized capacitor than a plain foil type of equivalent value but has the disadvantage of not being able to withstand high DC currents compared to the plain type. Also their tolerance range is quite large at up to 20%. Typical values of capacitance for an aluminium electrolytic capacitor range from 1uF up to 47,000uF.

Etched foil electrolytic’s are best used in coupling, DC blocking and by-pass circuits while plain foil types are better suited as smoothing capacitors in power supplies. But aluminium electrolytic’s are “polarised” devices so reversing the applied voltage on the leads will cause the insulating layer within the capacitor to become destroyed along with the capacitor. However, the electrolyte used within the capacitor helps heal a damaged plate if the damage is small.

Since the electrolyte has the properties to self-heal a damaged plate, it also has the ability to re-anodize the foil plate. As the anodizing process can be reversed, the electrolyte has the ability to remove the oxide coating from the foil as would happen if the capacitor was connected with a reverse polarity. Since the electrolyte has the ability to conduct electricity, if the aluminium oxide layer was removed or destroyed, the capacitor would allow current to pass from one plate to the other destroying the capacitor, “so be aware”.

2.Tantalum Electrolytic Capacitors

Tantalum Electrolytic Capacitors and **Tantalum Beads**, are available in both wet (foil) and dry (solid) electrolytic types with the dry or solid tantalum being the most common. Solid tantalum capacitors use manganese dioxide as their second terminal and are physically smaller than the equivalent aluminium capacitors.

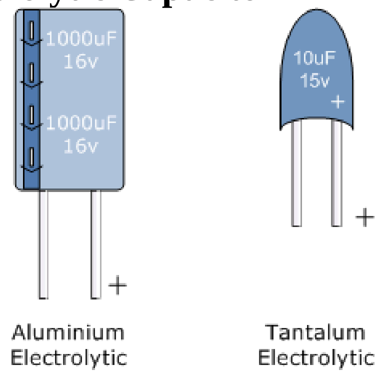
The dielectric properties of tantalum oxide is also much better than those of aluminium oxide giving a lower leakage currents and better capacitance stability which makes them suitable for use in blocking, by-passing, decoupling, filtering and timing applications.

Also, **Tantalum Capacitors** although polarised, can tolerate being connected to a reverse voltage much more easily than the aluminium types but are rated at much lower working voltages. Solid tantalum capacitors are usually used in circuits where the AC voltage is small compared to the DC voltage.

However, some tantalum capacitor types contain two capacitors in-one, connected negative-to-negative to form a “non-polarised” capacitor for use in low voltage AC circuits as a non-polarised device.

Generally, the positive lead is identified on the capacitor body by a polarity mark, with the body of a tantalum bead capacitor being an oval geometrical shape. Typical values of capacitance range from 47nF to 470uF.

Aluminium & Tantalum Electrolytic Capacitor



Electrolytic's are widely used capacitors due to their low cost and small size but there are three easy ways to destroy an electrolytic capacitor:

- Over-voltage–excessive voltage will cause current to leak through the dielectric resulting in a short circuit condition.
- Reversed Polarity–reverse voltage will cause self-destruction of the oxide layer and failure.
- Over Temperature–excessive heat dries out the electrolytic and shortens the life of an electrolytic capacitor.

In the next tutorial about Capacitors, we will look at some of the main characteristics to show that there is more to the **Capacitor** than just voltage and capacitance.

https://www.electronics-tutorials.ws/capacitor/cap_3.html

Capacitor Characteristics

The characteristics of a capacitors define its temperature, voltage rating and capacitance range as well as its use in a particular application.

There are a bewildering array of capacitor characteristics and specifications associated with the humble capacitor and reading the information printed onto the body of a capacitor can sometimes be difficult to understand especially when colours or numeric codes are used.

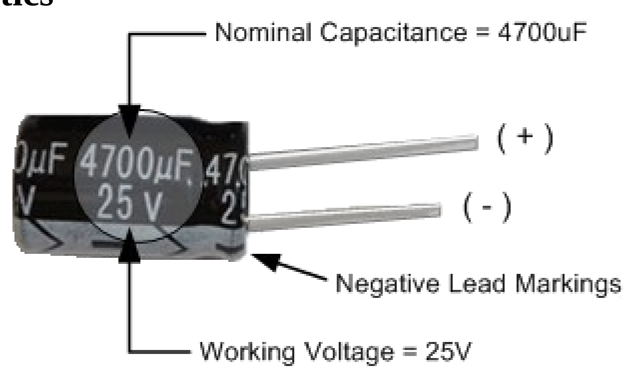
Each family or type of capacitor uses its own unique set of capacitor characteristics and identification system with some systems being easy to understand, and others that use misleading letters, colours or symbols.

The best way to figure out which capacitor characteristics the label means is to first figure out what type of family the capacitor belongs to whether it is ceramic, film, plastic or electrolytic and from that it may be easier to identify the particular capacitor characteristics.

Even though two capacitors may have exactly the same capacitance value, they may have different voltage ratings. If a smaller rated voltage capacitor is substituted in place of a higher rated voltage capacitor, the increased voltage may damage the smaller capacitor.

Also we remember from the last tutorial that with a polarised electrolytic capacitor, the positive lead must go to the positive connection and the negative lead to the negative connection otherwise it may again become damaged. So it is always better to substitute an old or damaged capacitor with the same type as the specified one. An example of capacitor markings is given below.

Capacitor Characteristics



The capacitor, as with any other electronic component, comes defined by a series of characteristics. These **Capacitor Characteristics** can always be found in the data sheets that the capacitor manufacturer provides to us so here are just a few of the more important ones.

1. Nominal Capacitance, (C)

The nominal value of the **Capacitance**, C of a capacitor is the most important of all capacitor characteristics. This value measured in pico-Farads (pF), nano-Farads (nF) or micro-Farads (μF) and is marked onto the body of the capacitor as numbers, letters or coloured bands.

The capacitance of a capacitor can change value with the circuit frequency (Hz) and with the ambient temperature. Smaller ceramic capacitors can have a nominal value as low as one pico-Farad, (1pF) while larger electrolytic's can have a nominal capacitance value of up to one Farad, (1F).

All capacitors have a tolerance rating that can range from -20% to as high as +80% for aluminium electrolytic's affecting its actual or real value. The choice of capacitance is determined by the circuit configuration but the value read on the side of a capacitor may not necessarily be its actual value.

2. Working Voltage, (WV)

The **Working Voltage** is another important capacitor characteristic that defines the maximum continuous voltage either DC or AC that can be applied to the capacitor without failure during its working life. Generally, the working voltage printed onto the side of a capacitors body refers to its DC working voltage, (WVDC).

DC and AC voltage values are usually not the same for a capacitor as the AC voltage value refers to the r.m.s. value and NOT the maximum or peak value which is 1.414 times greater. Also, the specified DC working voltage is valid within a certain temperature range, normally -30°C to +70°C.

Any DC voltage in excess of its working voltage or an excessive AC ripple current may cause failure. It follows therefore, that a capacitor will have a longer working life if operated in a cool environment and within its rated voltage. Common working DC voltages are 10V, 16V, 25V, 35V, 50V, 63V, 100V, 160V, 250V, 400V and 1000V and are printed onto the body of the capacitor.

3. Tolerance, (±%)

As with resistors, capacitors also have a **Tolerance** rating expressed as a plus-or-minus value either in picofarad's (±pF) for low value capacitors generally less than 100pF or as a percentage (±%) for higher value capacitors generally higher than 100pF.

The tolerance value is the extent to which the actual capacitance is allowed to vary from its nominal value and can range anywhere from -20% to +80%. Thus a 100μF capacitor with a ±20% tolerance could legitimately vary from 80μF to 120μF and still remain within tolerance.

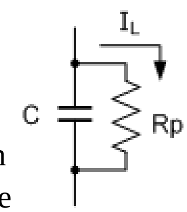
Capacitors are rated according to how near to their actual values they are compared to the rated nominal capacitance with coloured bands or letters used to indicated their actual tolerance. The most common tolerance variation for capacitors is 5% or 10% but some plastic capacitors are rated as low as ±1%.

4. Leakage Current

The dielectric used inside the capacitor to separate the conductive plates is not a perfect insulator resulting in a very small current flowing or “leaking” through the dielectric due to the influence of the powerful electric fields built up by the charge on the plates when applied to a constant supply voltage.

This small DC current flow in the region of nano-amps (nA) is called the capacitors **Leakage Current**. Leakage current is a result of electrons physically making their way through the dielectric medium, around its edges or across its leads and which will over time fully discharging the capacitor if the supply voltage is removed.

When the leakage is very low such as in film or foil type capacitors it is generally referred to as “insulation resistance” (R_p) and can be expressed as a high value resistance in parallel with the capacitor as shown. When the leakage current is high as in electrolytic’s it is referred to as a “leakage current” as electrons flow directly through the electrolyte.



Leakage Model

Capacitor leakage current is an important parameter in amplifier coupling circuits or in power supply circuits, with the best choices for coupling and/or storage applications being Teflon and the other plastic capacitor types (polypropylene, polystyrene, etc) because the lower the dielectric constant, the higher the insulation resistance.

Electrolytic-type capacitors (tantalum and aluminium) on the other hand may have very high capacitances, but they also have very high leakage currents (typically of the order of about 5-20 μA per μF) due to their poor isolation resistance, and are therefore not suited for storage or coupling applications. Also, the flow of leakage current for aluminium electrolytic’s increases with temperature.

5. Working Temperature, (T)

Changes in temperature around the capacitor affect the value of the capacitance because of changes in the dielectric properties. If the air or surrounding temperature becomes to hot or to cold the capacitance value of the capacitor may change so much as to affect the correct operation of the circuit. The normal working range for most capacitors is -30^{o}C to +125^{o}C with nominal voltage ratings given for a **Working Temperature** of no more than +70^{o}C especially for the plastic capacitor types.

Generally for electrolytic capacitors and especially aluminium electrolytic capacitor, at high temperatures (over +85^{o}C the liquids within the electrolyte can be lost to evaporation, and the body of the capacitor (especially the small sizes) may become deformed due to the internal pressure and leak outright. Also, electrolytic capacitors can not be used at low temperatures, below about -10^{o}C, as the electrolyte jelly freezes.

6. Temperature Coefficient, (TC)

The **Temperature Coefficient** of a capacitor is the maximum change in its capacitance over a specified temperature range. The temperature coefficient of a capacitor is generally expressed linearly as parts per million per degree centigrade (PPM/^{o}C), or as a percent change over a particular range of temperatures. Some capacitors are non linear (Class 2 capacitors) and increase their value as the temperature rises giving them a temperature coefficient that is expressed as a positive “P”.

Some capacitors decrease their value as the temperature rises giving them a temperature coefficient that is expressed as a negative “N”. For example “P100” is +100 ppm/^{o}C or “N200”, which is -200 ppm/^{o}C etc. However, some capacitors do not change their value and remain constant over a certain temperature range, such capacitors have a zero temperature coefficient or “NPO”. These types of capacitors such as Mica or Polyester are generally referred to as Class 1 capacitors.

Most capacitors, especially electrolytic’s lose their capacitance when they get hot but temperature compensating capacitors are available in the range of at least P1000 through to N5000 (+1000 ppm/^{o}C through to -5000 ppm/^{o}C). It is also possible to connect a capacitor with a positive temperature coefficient in series or parallel with a capacitor having a negative temperature coefficient the net result being that the two opposite effects will cancel each other out over a certain range of temperatures. Another useful application of temperature coefficient capacitors is to use them to cancel out the effect of temperature on other components within a circuit, such as inductors or resistors etc.

7. Polarization

Capacitor **Polarization** generally refers to the electrolytic type capacitors but mainly the Aluminium Electrolytic’s, with regards to their electrical connection. The majority of electrolytic capacitors are polarized types, that is the voltage connected to the capacitor terminals must have the correct polarity, i.e. positive to positive and negative to negative.

Incorrect polarization can cause the oxide layer inside the capacitor to break down resulting in very large currents flowing through the device resulting in destruction as we have mentioned earlier.

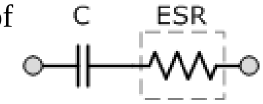
The majority of electrolytic capacitors have their negative, -ve terminal clearly marked with either a black stripe, band, arrows or chevrons down one side of their body as shown, to prevent any incorrect connection to the DC supply.

Some larger electrolytic’s have their metal can or body connected to the negative terminal but high voltage types have their metal can insulated with the electrodes being brought out to separate spade or screw terminals for safety.

Also, when using aluminium electrolytic’s in power supply smoothing circuits care should be taken to prevent the sum of the peak DC voltage and AC ripple voltage from becoming a “reverse voltage”.

8. Equivalent Series Resistance, (ESR)

The **Equivalent Series Resistance** or **ESR**, of a capacitor is the AC impedance of the capacitor when used at high frequencies and includes the resistance of the dielectric material, the DC resistance of the terminal leads, the DC resistance of



ESR Model

the connections to the dielectric and the capacitor plate resistance all measured at a particular frequency and temperature.

In some ways, ESR is the opposite of the insulation resistance which is presented as a pure resistance (no capacitive or inductive reactance) in parallel with the capacitor. An ideal capacitor would have only capacitance but ESR is presented as a pure resistance (less than 0.1Ω) in series with the capacitor (hence the name Equivalent Series Resistance), and which is frequency dependent making it a “DYNAMIC” quantity.

As ESR defines the energy losses of the “equivalent” series resistance of a capacitor it must therefore determine the capacitor’s overall I^2R heating losses especially when used in power and switching circuits.

Capacitors with a relatively high ESR have less ability to pass current to and from its plates to the external circuit because of their longer charging and discharging RC time constant. The ESR of electrolytic capacitors increases over time as their electrolyte dries out. Capacitors with very low ESR ratings are available and are best suited when using the capacitor as a filter.

As a final note, capacitors with small capacitance’s (less than 0.01μF) generally do not pose much danger to humans. However, when their capacitance’s start to exceed 0.1μF, touching the capacitor leads can be a shocking experience.

Capacitors have the ability to store an electrical charge in the form of a voltage across themselves even when there is no circuit current flowing, giving them a sort of memory with large electrolytic type reservoir capacitors found in television sets, photo flashes and capacitor banks potentially storing a lethal charge.

As a general rule of thumb, never touch the leads of large value capacitors once the power supply is removed. If you are unsure about their condition or the safe handling of these large capacitors, seek help or expert advice before handling them.

We have listed here only a few of the many capacitor characteristics available to both identify and define its operating conditions and in the next tutorial in our section about Capacitors, we look at how capacitors store electrical charge on their plates and use it to calculate its capacitance value.

https://www.electronics-tutorials.ws/capacitor/cap_4.html

Capacitance and Charge

Capacitors store electrical energy on their plates in the form of an electrical charge.

Capacitors consist of two parallel conductive plates (usually a metal) which are prevented from touching each other (separated) by an insulating material called the “dielectric”. When a voltage is applied to these plates an electrical current flows charging up one plate with a positive charge with respect to the supply voltage and the other plate with an equal and opposite negative charge.

Then, a capacitor has the ability of being able to store an electrical charge Q (units in **Coulombs**) of electrons. When a capacitor is fully charged there is a potential difference, (p.d.) between its plates, and the larger the area of the plates and/or the smaller the distance between them (known as separation) the greater will be the charge that the capacitor can hold and the greater will be its **Capacitance**.

The capacitors ability to store this electrical charge (Q) between its plates is proportional to the applied voltage, V for a capacitor of known capacitance in Farads. Note that capacitance C is ALWAYS positive and never negative.

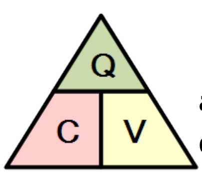
The greater the applied voltage the greater will be the charge stored on the plates of the capacitor. Likewise, the smaller the applied voltage the smaller the charge. Therefore, the actual charge Q on the plates of the capacitor and can be calculated as:

Charge on a Capacitor

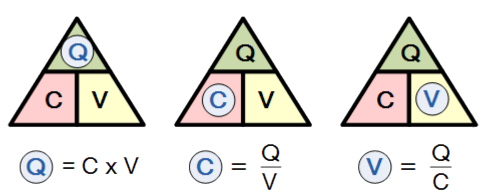
$$Q = C \times V$$

Where: Q (Charge, in Coulombs) = C (Capacitance, in Farads) x V (Voltage, in Volts)

It is sometimes easier to remember this relationship by using pictures. Here the three quantities of Q, C and V have been superimposed into a triangle giving charge at the top with capacitance and voltage at the bottom. This arrangement represents the actual position of each quantity in the *Capacitor Charge* formulas.



and transposing the above equation gives us the following combinations of the same equation:



<u>Units of:</u> Q measured in Coulombs, V in volts and C in Farads.

Then from above we can define the unit of **Capacitance** as being a constant of proportionality being equal to the coulomb/volt which is also called a **Farad**, unit F.

As capacitance represents the capacitors ability (capacity) to store an electrical charge on its plates we can define one Farad as the "*capacitance of a capacitor which requires a charge of one coulomb to establish a potential difference of one volt between its plates*" as firstly described by Michael Faraday. So the larger the capacitance, the higher is the amount of charge stored on a capacitor for the same amount of voltage.

The ability of a capacitor to store a charge on its conductive plates gives it its **Capacitance** value. Capacitance can also be determined from the dimensions or area, A of the plates and the properties of the dielectric material between the plates. A measure of the dielectric material is given by the permittivity, (ε), or the dielectric constant. So another way of expressing the capacitance of a capacitor is:

Capacitor with Air as its dielectric

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

Capacitor with a Solid as its dielectric

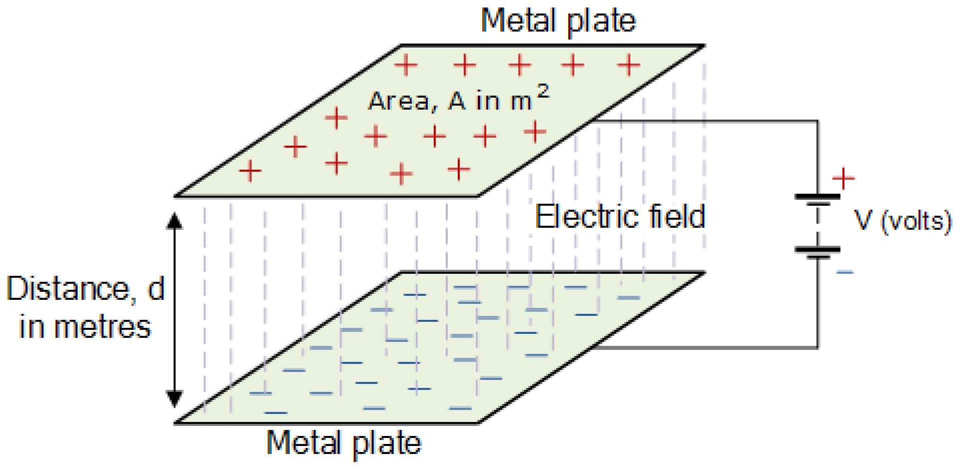
$$C = \frac{Q}{V} = \varepsilon_0 \varepsilon_r \frac{A}{d}$$

Where A is the area of the plates in square metres, m^2 with the larger the area, the more charge the capacitor can store. d is the distance or separation between the two plates.

The smaller is this distance, the higher is the ability of the plates to store charge, since the -ve charge on the -Q charged plate has a greater effect on the +Q charged plate, resulting in more electrons being repelled off of the +Q charged plate, and thus increasing the overall charge.

ε_0 (epsilon) is the value of the permittivity for air which is 8.854 x 10^{-12} F/m, and ε_r is the permittivity of the dielectric medium used between the two plates.

Parallel Plate Capacitor



We have said previously that the capacitance of a parallel plate capacitor is proportional to the surface area A and inversely proportional to the distance, d between the two plates and this is true for dielectric medium of air. However, the capacitance value of a capacitor can be increased by inserting a solid medium in between the conductive plates which has a dielectric constant greater than that of air.

Typical values of epsilon ε for various commonly used dielectric materials are: Air = 1.0, Paper = 2.5 – 3.5, Glass = 3 – 10, Mica = 5 – 7 etc.

The factor by which the dielectric material, or insulator, increases the capacitance of the capacitor compared to air is known as the **Dielectric Constant**, (**k**). "k" is the ratio of the permittivity of the dielectric medium being used to the permittivity of free space otherwise known as a vacuum.

Therefore, all the capacitance values are related to the permittivity of vacuum. A dielectric material with a high dielectric constant is a better insulator than a dielectric material with a lower dielectric constant. Dielectric constant is a dimensionless quantity since it is relative to free space.

Capacitance Example No1

A parallel plate capacitor consists of two plates with a total surface area of 100 cm^2. What will be the capacitance in pico-Farads, (pF) of the capacitor if the plate separation is 0.2 cm, and the dielectric medium used is air.

$$C = \varepsilon\frac{A}{d}, \quad \varepsilon = 8.85\,\mathrm{pF/m}$$

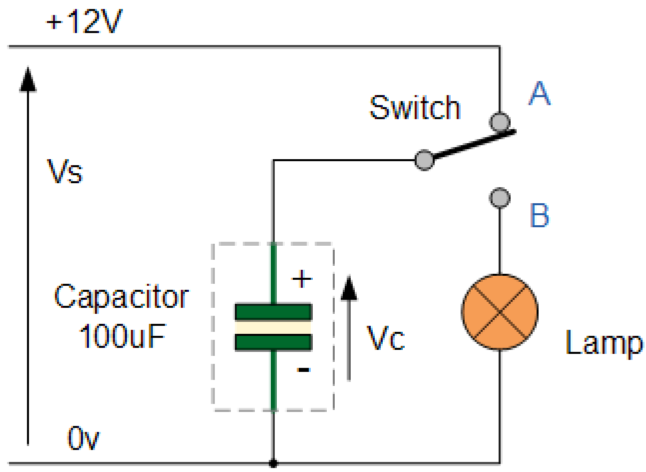
$$A = 100\,\mathrm{cm}^2 = 0.01\,\mathrm{m}^2, \quad d = 0.2\,\mathrm{cm} = 0.002\,\mathrm{m}$$

$$\therefore\ C = 8.85\times10^{-12}\times\frac{0.01\,\mathrm{m}^2}{0.002\,\mathrm{m}} = 44\,\mathrm{pF}$$

then the value of the capacitor is 44pF.

Charging & Discharging of a Capacitor

Consider the following circuit.



Assume that the capacitor is fully discharged and the switch connected to the capacitor has just been moved to position A. The voltage across the 100uf capacitor is zero at this point and a charging current (*i*) begins to flow charging up the capacitor exponentially until the voltage across the plates is very nearly equal to the 12v supply voltage. After 5 time constants the current becomes a trickle charge and the capacitor is said to be "fully-charged". Then, $V_C = V_S = 12$ volts.

Once the capacitor is "fully-charged" in theory it will maintain its state of voltage charge even when the supply voltage has been disconnected as they act as a sort of temporary storage device. However, while this may be true of an "ideal" capacitor, a real capacitor will slowly discharge itself over a long period of time due to the internal leakage currents flowing through the dielectric.

This is an important point to remember as large value capacitors connected across high voltage supplies can still maintain a significant amount of charge even when the supply voltage is switched "OFF".

If the switch was disconnected at this point, the capacitor would maintain its charge indefinitely, but due to internal leakage currents flowing across its dielectric the capacitor would very slowly begin to discharge itself as the electrons passed through the dielectric. The time taken for the capacitor to discharge down to 37% of its supply voltage is known as its Time Constant.

If the switch is now moved from position A to position B, the fully charged capacitor would start to discharge through the lamp now connected across it, illuminating the lamp until the capacitor was fully discharged as the element of the lamp has a resistive value.

The brightness of the lamp and the duration of illumination would ultimately depend upon the capacitance value of the capacitor and the resistance of the lamp (t = R*C). The larger the value of the capacitor the brighter and longer will be the illumination of the lamp as it could store more charge.

Capacitor Charge Example No2

Calculate the charge in the above capacitor circuit.

$$Q = C \times V$$

$$Q = 100\mu F \times 12v = 1.2 \times 10^{-3} = 1.2mC$$

then the charge on the capacitor is 1.2 millicoulombs.

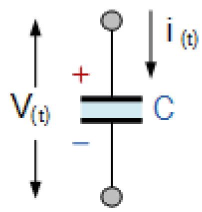
Current through a Capacitor

Electrical current can not actually flow through a capacitor as it does a resistor or inductor due to the insulating properties of the dielectric material between the two plates. However, the charging and discharging of the two plates gives the effect that current is flowing.

The current that flows through a capacitor is directly related to the charge on the plates as current is the rate of flow of charge with respect to time. As the capacitors ability to store charge (Q) between its plates is proportional to the applied voltage (V), the relationship between the current and the voltage that is applied to the plates of a capacitor becomes:

Current-Voltage (I-V) Relationship

$$i_{(t)} = C\frac{dv}{dt}$$



As the voltage across the plates increases (or decreases) over time, the current flowing through the capacitance deposits (or removes) charge from its plates with the amount of charge being proportional to the applied voltage. Then both the current and voltage applied to a capacitance are functions of time and are denoted by the symbols, $i_{(t)}$ and $v_{(t)}$.

However, from the above equation we can also see that if the voltage remains constant, the charge will become constant and therefore the current will be zero!. In other words, no change in voltage, no movement of charge and no flow of current. This is why a capacitor appears to “block” current flow when connected to a steady state DC voltage.

The Farad

We now know that the ability of a capacitor to store a charge gives it its capacitance value C, which has the unit of the **Farad, F**. But the farad is an extremely large unit on its own making it impractical to use, so sub-multiple’s or fractions of the standard Farad unit are used instead.

To get an idea of how big a Farad really is, the surface area of the plates required to produce a capacitor with a value of just one Farad with a reasonable plate separation of just say 1mm operating in a vacuum. If we rearranging the equation for capacitance above this would give us a plate area of:

$$\mathbf{A = Cd \div 8.85pF/m = (1 \times 0.001) \div 8.85{\times}10^{-12} = 112{,}994{,}350\ m^2}$$

or 113 million m^2 which would be equivalent to a plate of more than 10 kilometres x 10 kilometres (over 6 miles) square. That's huge.

Capacitors which have a value of one Farad or more tend to have a solid dielectric and as "One Farad" is such a large unit to use, prefixes are used instead in electronic formulas with capacitor values given in micro-Farads (μF), nano-Farads (nF) and the pico-Farads (pF). For example:

Sub-units of the Farad

$$\text{microfarad, } (\mu F) = \frac{1}{1{,}000{,}000} F = 1{\times}10^{-6} F$$

$$\text{nanofarad, } (nF) = \frac{1}{1{,}000{,}000{,}000} F = 1{\times}10^{-9} F$$

$$\text{picofarad, } (pF) = \frac{1}{1{,}000{,}000{,}000{,}000} F = 1{\times}10^{-12} F$$

Convert the following capacitance values:

a) 22nF to μF, b) 0.2μF to nF, c) 550pF to μF

a) 22nF = 0.022μF

b) 0.2μF = 200nF

c) 550pF = 0.00055μF

While one Farad is a large value on its own, capacitors are now commonly available with capacitance values of many hundreds of Farads and have names to reflect this of "Super-capacitors" or "Ultra-capacitors".

These capacitors are electrochemical energy storage devices which utilise a high surface area of their carbon dielectric to deliver much higher energy densities than conventional capacitors and as capacitance is proportional to the surface area of the carbon, the thicker the carbon the more capacitance it has.

Low voltage (from about 3.5V to 5.5V) super-capacitors are capable of storing large amounts of charge due to their high capacitance values as the energy stored in a capacitor is equal to 1/2(C x V^2).

Low voltage super-capacitors are commonly used in portable hand held devices to replace large, expensive and heavy lithium type batteries as they give battery-like storage and discharge characteristics making them ideal for use as an alternative power source or for memory backup. Super-capacitors used in hand held devices are usually charged using solar cells fitted to the device.

Ultra-capacitor are being developed for use in hybrid electric cars and alternative energy applications to replace large conventional batteries as well as DC smoothing applications in vehicle audio and video systems. Ultra-capacitors can be recharged quickly and have very high energy storage densities making them ideal for use in electric vehicle applications.

Energy in a Capacitor

When a capacitor charges up from the power supply connected to it, an electrostatic field is established which stores energy in the capacitor. The amount of energy in **Joules** that is stored in this electrostatic field is equal to the energy the voltage supply exerts to maintain the charge on the plates of the capacitor and is given by the formula:

$$\text{Energy, } W = \frac{1}{2}CV^2 \text{ or } \frac{CV^2}{2} \text{ in Joules, (j)}$$

so the energy stored in the 100uF capacitor circuit above is calculated as:

$$\text{Energy, } W = \frac{CV^2}{2} = \frac{100\times10^{-6}\times12^2}{2} = 7.2\text{mJ}$$

The next tutorial in our section about Capacitors, we look at Capacitor Colour Codes and see the different ways that the capacitance and voltage values of the capacitor are marked onto its body.

https://www.electronics-tutorials.ws/capacitor/cap_5.html

Capacitor Colour Codes

Generally, the actual values of Capacitance, Voltage or Tolerance are marked onto the body of the capacitors in the form of alphanumeric characters.

However, when the value of the capacitance is of a decimal value problems arise with the marking of the “Decimal Point” as it could easily not be noticed resulting in a misreading of the actual capacitance value. Instead letters such as p (pico) or n (nano) are used in place of the decimal point to identify its position and the weight of the number.

For example, a capacitor can be labelled as, n47 = 0.47nF, 4n7 = 4.7nF or 47n = 47nF and so on. Also, sometimes capacitors are marked with the capital letter K to signify a value of one thousand pico-Farads, so for example, a capacitor with the markings of 100K would be 100 x 1000pF or 100nF.

To reduce the confusion regarding letters, numbers and decimal points, an International colour coding scheme was developed many years ago as a simple way of identifying capacitor values and tolerances. It consists of coloured bands (in spectral order) known commonly as the **Capacitor Colour Code** system and whose meanings are illustrated below:

Capacitor Colour Code Table

Band Colour	Digit A	Digit B	Multiplier D	Tolerance (T) > 10pf	Tolerance (T) < 10pf	Temperature Coefficient (TC)
Black	0	0	x1	± 20%	± 2.0pF	
Brown	1	1	x10	± 1%	± 0.1pF	-33×10^{-6}
Red	2	2	x100	± 2%	± 0.25pF	-75×10^{-6}
Orange	3	3	x1,000	± 3%		-150×10^{-6}
Yellow	4	4	x10,000	± 4%		-220×10^{-6}
Green	5	5	x100,000	± 5%	± 0.5pF	-330×10^{-6}
Blue	6	6	x1,000,000			-470×10^{-6}
Violet	7	7				-750×10^{-6}
Grey	8	8	x0.01	+80%,-20%		
White	9	9	x0.1	± 10%	± 1.0pF	
Gold			x0.1	± 5%		
Silver			x0.01	± 10%		

Capacitor Voltage Colour Code Table

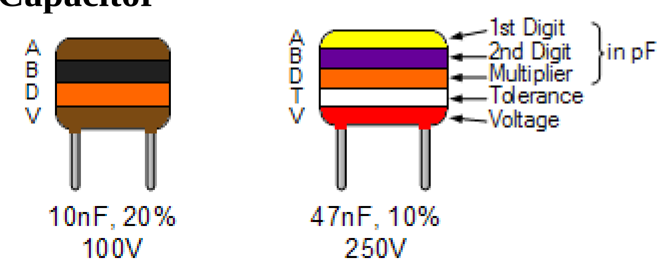
Band Colour	Voltage Rating (V)				
	Type J	Type K	Type L	Type M	Type N
Black	4	100		10	10
Brown	6	200	100	1.6	
Red	10	300	250	4	35
Orange	15	400		40	
Yellow	20	500	400	6.3	6
Green	25	600		16	15
Blue	35	700	630		20
Violet	50	800			
Grey		900		25	25
White	3	1000		2.5	3
Gold		2000			
Silver					

Capacitor Voltage Reference

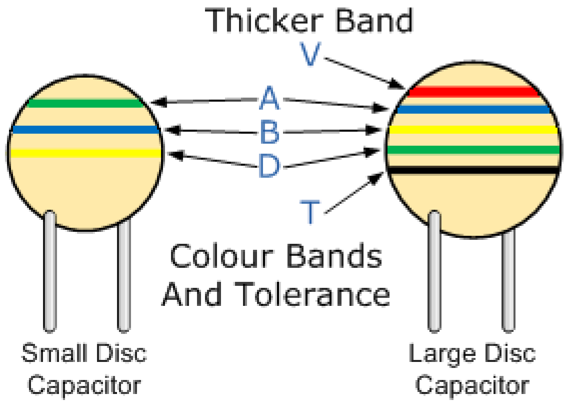
- Type J – Dipped Tantalum Capacitors.
- Type K – Mica Capacitors.
- Type L – Polyester/Polystyrene Capacitors.
- Type M – Electrolytic 4 Band Capacitors.
- Type N – Electrolytic 3 Band Capacitors.

An example of the use of capacitor colour codes is given as:

Metalised Polyester Capacitor



Disc & Ceramic Capacitor



The **Capacitor Colour Code** system was used for many years on unpolarised polyester and mica moulded capacitors. This system of colour coding is now obsolete but there are still many “old” capacitors around. Nowadays, small capacitors such as film or disk types conform to the BS1852 Standard and its new replacement, BS EN 60062, were the colours have been replaced by a letter or number coded system.

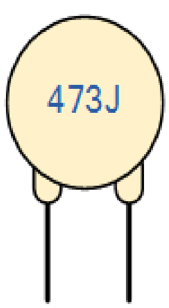
Generally the code consists of 2 or 3 numbers and an optional tolerance letter code to identify the tolerance. Where a two number code is used the value of the capacitor only is given in picofarads, for example, 47 = 47 pF and 100 = 100pF etc. A three letter code consists of the two value digits and a multiplier much like the resistor colour codes in the resistors section.

For example, the digits 471 = 47*10 = 470pF. Three digit codes are often accompanied by an additional tolerance letter code as given below.

Capacitor Tolerance Letter Codes Table

	Letter	B	C	D	F	G	J	K	M	Z
Tolerance	C <10pF ±pF	0.1	0.25	0.5	1	2				
	C >10pF ±%			0.5	1	2	5	10	20	+80 -20

Consider the capacitor below:



The capacitor on the left is of a ceramic disc type capacitor that has the code 473J printed onto its body. Then the 4 = 1st digit, the 7 = 2nd digit, the 3 is the multiplier in pico-Farads, pF and the letter J is the tolerance and this translates to: 47pF * 1,000 (3 zero’s) = 47,000 pF, 47nF or 0.047uF the J indicates a tolerance of +/- 5%

Then by just using numbers and letters as codes on the body of the capacitor we can easily determine the value of its capacitance either in Pico-farad’s, Nano-farads or Micro-farads and a list of these “international” codes is given in the following table along with their equivalent capacitances.

Capacitor Letter Codes Table

Picofarad (pF)	Nanofarad (nF)	Microfarad (uF)	Code	Picofarad (pF)	Nanofarad (nF)	Microfarad (uF)	Code
10	0.01	0.00001	100	4700	4.7	0.0047	472
15	0.015	0.000015	150	5000	5.0	0.005	502
22	0.022	0.000022	220	5600	5.6	0.0056	562
33	0.033	0.000033	330	6800	6.8	0.0068	682
47	0.047	0.000047	470	10000	10	0.01	103
100	0.1	0.0001	101	15000	15	0.015	153
120	0.12	0.00012	121	22000	22	0.022	223
130	0.13	0.00013	131	33000	33	0.033	333
150	0.15	0.00015	151	47000	47	0.047	473
180	0.18	0.00018	181	68000	68	0.068	683
220	0.22	0.00022	221	100000	100	0.1	104
330	0.33	0.00033	331	150000	150	0.15	154
470	0.47	0.00047	471	200000	200	0.2	254
560	0.56	0.00056	561	220000	220	0.22	224
680	0.68	0.00068	681	330000	330	0.33	334
750	0.75	0.00075	751	470000	470	0.47	474
820	0.82	0.00082	821	680000	680	0.68	684
1000	1.0	0.001	102	1000000	1000	1.0	105
1500	1.5	0.0015	152	1500000	1500	1.5	155
2000	2.0	0.002	202	2000000	2000	2.0	205
2200	2.2	0.0022	222	2200000	2200	2.2	225
3300	3.3	0.0033	332	3300000	3300	3.3	335

The next tutorial in our section about Capacitors, we look at connecting together Capacitor in Parallel and see that the total capacitance is the sum of the individual capacitors.

https://www.electronics-tutorials.ws/capacitor/cap_6.html

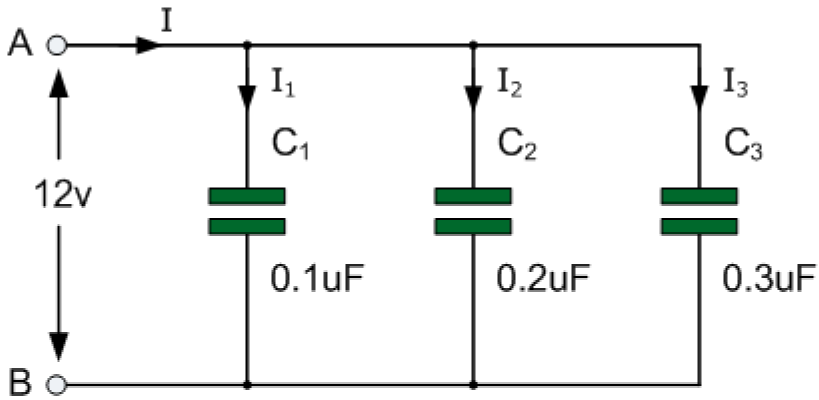
Capacitors in Parallel

Capacitors are connected together in parallel when both of its terminals are connected to each terminal of another capacitor.

The voltage (Vc) connected across all the capacitors that are connected in parallel is **THE SAME**. Then, **Capacitors in Parallel** have a "common voltage" supply across them giving:

$$\mathbf{V_{C1} = V_{C2} = V_{C3} = V_{AB} = 12V}$$

In the following circuit the capacitors, C_1, C_2 and C_3 are all connected together in a parallel branch between points A and B as shown.



When capacitors are connected together in parallel the total or equivalent capacitance, C_T in the circuit is equal to the sum of all the individual capacitors added together. This is because the top plate of capacitor, C_1 is connected to the top plate of C_2 which is connected to the top plate of C_3 and so on.

The same is also true of the capacitors bottom plates. Then it is the same as if the three sets of plates were touching each other and equal to one large single plate thereby increasing the effective plate area in m^2.

Since capacitance, C is related to plate area ($C = \varepsilon(A/d)$) the capacitance value of the combination will also increase. Then the total capacitance value of the capacitors connected together in parallel is actually calculated by adding the plate area together. In other words, the total capacitance is equal to the sum of all the individual capacitance's in parallel. You may have noticed that the total capacitance of parallel capacitors is found in the same way as the total resistance of series resistors.

The currents flowing through each capacitor and as we saw in the previous tutorial are related to the voltage. Then by applying Kirchoff's Current Law, (KCL) to the above circuit, we have

$$i_1 = C_1\frac{dv}{dt}, \quad i_2 = C_2\frac{dv}{dt}, \quad i_3 = C_3\frac{dv}{dt}$$

$$i_T = i_1 + i_2 + i_3$$

$$\therefore i_T = C_1\frac{dv}{dt} + C_2\frac{dv}{dt} + C_3\frac{dv}{dt}$$

and this can be re-written as:

$$i_T = \left(C_1 + C_2 + C_3\right)\frac{dv}{dt}$$

$$\text{or} \quad i_T = C_T\frac{dv}{dt}$$

Then we can define the total or equivalent circuit capacitance, C_T as being the sum of all the individual capacitance's add together giving us the generalized equation of:

Parallel Capacitors Equation

$$C_T = C_1 + C_2 + C_3 + \ldots\text{.etc}$$

When adding together capacitors in parallel, they must all be converted to the same capacitance units, whether it is μF, nF or pF. Also, we can see that the current flowing through the total capacitance value, C_T is the same as the total circuit current, i_T

We can also define the total capacitance of the parallel circuit from the total stored coulomb charge using the Q = CV equation for charge on a capacitors plates. The total charge Q_T stored on all the plates equals the sum of the individual stored charges on each capacitor therefore,

$$Q_T = Q_1 + Q_2 + Q_3 \quad \text{but,} \ Q = CV$$

$$\therefore Q_T = CV_T = CV_1 + CV_2 + CV_3$$

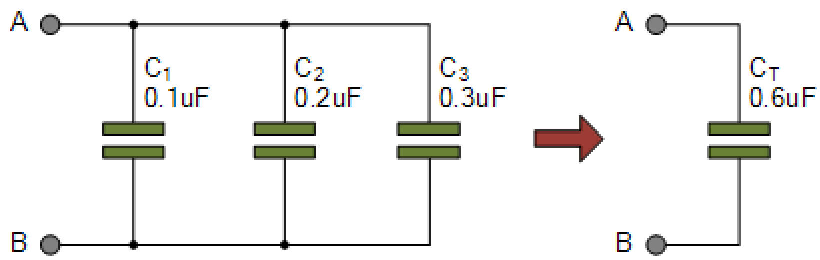
$$\text{or} \quad C_T = C_1 + C_2 + C_3$$

As the voltage, (V) is common for parallel connected capacitors, we can divide both sides of the above equation through by the voltage leaving just the capacitance and by simply adding together the value of the individual capacitances gives the total capacitance, C_T. Also, this equation is not dependent upon the number of **Capacitors in Parallel** in the branch, and can therefore be generalized for any number of N parallel capacitors connected together.

Capacitors in Parallel Example No1

So by taking the values of the three capacitors from the above example, we can calculate the total equivalent circuit capacitance C_T as being:

$$\mathbf{C_T = C_1 + C_2 + C_3 = 0.1uF + 0.2uF + 0.3uF = 0.6uF}$$



One important point to remember about parallel connected capacitor circuits, the total capacitance (C_T) of any two or more capacitors connected together in parallel will always be **GREATER** than the value of the largest capacitor in the group as we are adding together values. So in our example above C_T = 0.6μF whereas the largest value capacitor is only 0.3μF.

When 4, 5, 6 or even more capacitors are connected together the total capacitance of the circuit C_T would still be the sum of all the individual capacitors added together and as we know now, the total capacitance of a parallel circuit is always greater than the highest value capacitor.

This is because we have effectively increased the total surface area of the plates. If we do this with two identical capacitors, we have doubled the surface area of the plates which in turn doubles the capacitance of the combination and so on.

Capacitors in Parallel Example No2

Calculate the combined capacitance in micro-Farads (μF) of the following capacitors when they are connected together in a parallel combination:

- a) two capacitors each with a capacitance of 47nF
- b) one capacitor of 470nF connected in parallel to a capacitor of 1μF

a) Total Capacitance,

$$C_T = C_1 + C_2 = 47nF + 47nF = 94nF \text{ or } 0.094\mu F$$

b) Total Capacitance,

$C_T = C_1 + C_2 = 470nF + 1\mu F$

$$\text{therefore, } C_T = 470nF + 1000nF = 1470nF \text{ or } 1.47\mu F$$

So, the total or equivalent capacitance, C_T of an electrical circuit containing two or more **Capacitors in Parallel** is the sum of the all the individual capacitance's added together as the effective area of the plates is increased.

In our next tutorial about capacitors we look at connecting together Capacitors in Series and the affect this combination has on the circuits total capacitance, voltage and current.

https://www.electronics-tutorials.ws/capacitor/cap_7.html

Capacitors in Series

Capacitors are connected together in series when they are daisy chained together in a single line.

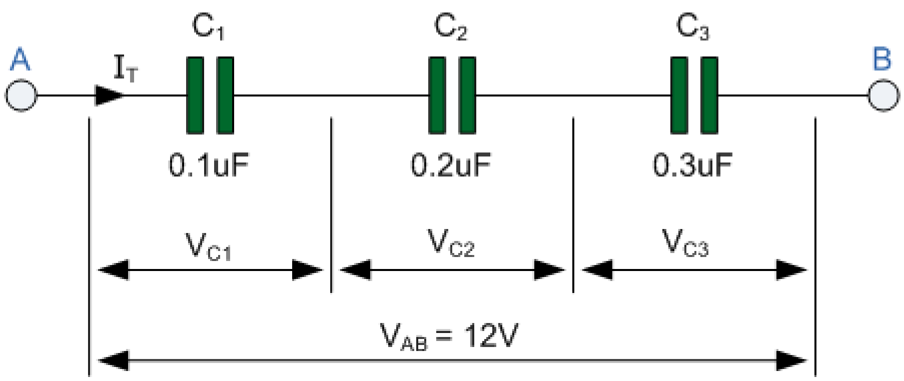
For series connected capacitors, the charging current (i_C) flowing through the capacitors is **THE SAME** for all capacitors as it only has one path to follow.

Then, **Capacitors in Series** all have the same current flowing through them as $i_T=i_1=i_2=i_3$ etc. Therefore each capacitor will store the same amount of electrical charge, Q on its plates regardless of its capacitance. This is because the charge stored by a plate of any one capacitor must have come from the plate of its adjacent capacitor. Therefore, capacitors connected together in series must have the same charge.

$$Q_T = Q_1 = Q_2 = Q_3 \text{ ….etc}$$

Consider the following circuit in which the three capacitors, C_1, $C_2$and $C_3$are all connected together in a series branch across a supply voltage between points A and B.

Capacitors in a Series Connection



In the previous parallel circuit we saw that the total capacitance, C_T of the circuit was equal to the sum of all the individual capacitors added together. In a series connected circuit however, the total or equivalent capacitance C_T is calculated differently.

In the series circuit above the right hand plate of the first capacitor, C_1 is connected to the left hand plate of the second capacitor, C_2 whose right hand plate is connected to the left hand plate of the third capacitor, C_3. Then this series connection means that in a DC connected circuit, capacitor C_2 is effectively isolated from the circuit.

The result of this is that the effective plate area has decreased to the smallest individual capacitance connected in the series chain. Therefore the voltage drop across each capacitor will be different depending upon the values of the individual capacitance's.

Then by applying Kirchhoff's Voltage Law, (KVL) to the above circuit, we get:

$$V_{AB} = V_{C1} + V_{C2} + V_{C3} = 12V$$

$$V_{C1} = \frac{Q_T}{C_1},\ V_{C2} = \frac{Q_T}{C_2},\ V_{C3} = \frac{Q_T}{C_3}$$

Since Q = C*V and rearranging for V = Q/C, substituting Q/C for each capacitor voltage V_C in the above KVL equation will give us:

$$V_{AB} = \frac{Q_T}{C_T} = \frac{Q_T}{C_1} + \frac{Q_T}{C_2} + \frac{Q_T}{C_3}$$

dividing each term through by Q gives

Series Capacitors Equation

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

When adding together **Capacitors in Series**, the reciprocal (1/C) of the individual capacitors are all added together (just like resistors in parallel) instead of the capacitance's themselves. Then the total value for capacitors in series equals the reciprocal of the sum of the reciprocals of the individual capacitances.

Capacitors in Series Example No1

Taking the three capacitor values from the above example, we can calculate the total equivalent capacitance, C_T for the three capacitors in series as being:

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

$$\left(\frac{1}{0.1\mu F} + \frac{1}{0.2\mu F} + \frac{1}{0.3\mu F}\right) = 18.33\times10^6$$

$$\frac{1}{C_T} = 18.33\times10^6 \quad \therefore\ C_T = \frac{1}{18.33\times10^6} = 0.055\mu F$$

One important point to remember about capacitors that are connected together in a series configuration. The total circuit capacitance (C_T) of any number of capacitors connected together in series will always be **LESS** than the value of the smallest capacitor in the series string. In our example above, the total capacitance$C_T$was calculated as being0.055μF but the value of the smallest capacitor in the series chain is only 0.1μF.

This reciprocal method of calculation can be used for calculating any number of individual capacitors connected together in a single series network. If however, there are only two capacitors in series, then a much simpler and quicker formula can be used. This is given as:

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

If the two series connected capacitors are equal and of the same value, that is: C_1=C_2, we can simplify the above equation further as follows to find the total capacitance of the series combination.

$$C_T = \frac{C^2}{2C} = \frac{C}{2} = \frac{1}{2}C$$

Then we can see that if and only if the two series connected capacitors are the same and equal, then the total capacitance, C_T will be exactly equal to one half of the capacitance value, that is: C/2.

With series connected resistors, the sum of all the voltage drops across the series circuit will be equal to the applied voltage V_S (Kirchhoff's Voltage Law) and this is also true about capacitors in series.

With series connected capacitors, the capacitive reactance of the capacitor acts as an impedance due to the frequency of the supply. This capacitive reactance produces a voltage drop across each capacitor, therefore the series connected capacitors act as a capacitive voltage divider network.

The result is that the voltage divider formula applied to resistors can also be used to find the individual voltages for two capacitors in series. Then:

$$V_{CX} = V_S \frac{C_T}{C_X}$$

Where: C_X is the capacitance of the capacitor in question, V_S is the supply voltage across the series chain and V_{CX} is the voltage drop across the target capacitor.

Capacitors in Series Example No2

Find the overall capacitance and the individual rms voltage drops across the following sets of two capacitors in series when connected to a 12V AC supply.

- a)two capacitors each with a capacitance of 47nF
- b)one capacitor of 470nF connected in series to a capacitor of 1μF

a) Total Equal Capacitance,

$$C_T = \frac{C_1 \times C_2}{C_1 + C_2} = \frac{47nF \times 47nF}{47nF + 47nF} = 23.5nF$$

Voltage drop across the two identical 47nF capacitors,

$$V_{C1} = \frac{C_T}{C_1} \times V_T = \frac{23.5nF}{47nF} \times 12V = 6volts$$

$$V_{C2} = \frac{C_T}{C_2} \times V_T = \frac{23.5nF}{47nF} \times 12V = 6volts$$

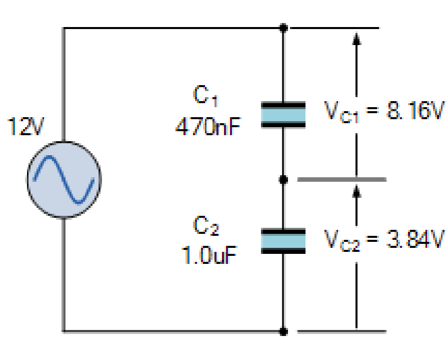
b) Total Unequal Capacitance,

$$C_T = \frac{C_1 \times C_2}{C_1 + C_2} = \frac{470nF \times 1uF}{470nF + 1uF} = 320nF$$

Voltage drop across the two non-identical Capacitors: C_1=470nF and C_2=1μF.

$$V_{C1} = \frac{C_T}{C_1} \times V_T = \frac{320nF}{470nF} \times 12 = 8.16volts$$

$$V_{C2} = \frac{C_T}{C_2} \times V_T = \frac{320nF}{1uF} \times 12 = 3.84volts$$



Since Kirchhoff's voltage law applies to this and every series connected circuit, the total sum of the individual voltage drops will be equal in value to the supply voltage, V_S. Then 8.16+3.84=12V.

Note also that if the capacitor values are the same, 47nF in our first example, the supply voltage will be divided equally across each capacitor as shown. This is because each capacitor in the series chain shares an equal and exact amount of charge (Q=CxV=0.564μC) and therefore has half (or percentage fraction for more than two capacitors) of the applied voltage, V_S.

However, when the series capacitor values are different, the larger value capacitor will charge itself to a lower voltage and the smaller value capacitor to a higher voltage, and in our second example above this was shown to be 3.84 and 8.16 volts respectively. This difference in voltage allows the capacitors to maintain the same amount of charge, Q on the plates of each capacitors as shown.

$$Q_{C1} = V_{C1} \times C_1 = 8.16V \times 470nF = 3.84\mu C$$

$$Q_{C2} = V_{C2} \times C_2 = 3.84V \times 1uF = 3.84\mu C$$

Note that the ratios of the voltage drops across the two capacitors connected in series will always remain the same regardless of the supply frequency as their reactance, X_C will remain proportionally the same.

Then the two voltage drops of 8.16 volts and 3.84 volts above in our simple example will remain the same even if the supply frequency is increased from 100Hz to 100kHz.

Although the voltage drops across each capacitor will be different for different values of capacitance, the coulomb charge across the plates will be equal because the same amount of current flow exists throughout a series circuit as all the capacitors are being supplied with the same number or quantity of electrons.

In other words, if the charge across each capacitors plates is the same, as Q is constant, then as its capacitance decreases the voltage drop across the capacitors plates increases, because the charge is large with respect to the capacitance. Likewise, a larger capacitance will result in a smaller voltage drop across its plates because the charge is small with respect to the capacitance.

Capacitors in Series Summary

Then to summarise, the total or equivalent capacitance, C_T of a circuit containing **Capacitors in Series** is the reciprocal of the sum of the reciprocals of all of the individual capacitance's added together.

Also for **capacitors connected in series**, all the series connected capacitors will have the same charging current flowing through them as $i_T=i_1=i_2=i_3$ etc. Two or more capacitors in series will always have equal amounts of coulomb charge across their plates.

As the charge, (Q) is equal and constant, the voltage drop across the capacitor is determined by the value of the capacitor only as V=Q ÷C. A small capacitance value will result in a larger voltage while a large value of capacitance will result in a smaller voltage drop.

https://www.electronics-tutorials.ws/capacitor/cap_8.html

Capacitance in AC Circuits

Capacitors that are connected to a sinusoidal supply produce reactance from the effects of supply frequency and capacitor size.

When capacitors are connected across a direct current DC supply voltage, their plates charge-up until the voltage value across the capacitor is equal to that of the externally applied voltage. The capacitor will hold this charge indefinitely, acting like a temporary storage device as long as the applied voltage is maintained.

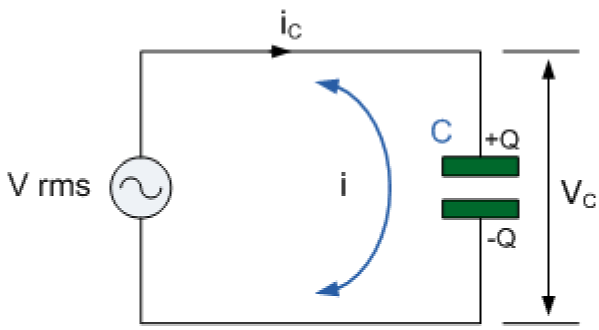
During this charging process, an electric current (i) flows into the capacitor which results in its plates beginning to hold an electrostatic charge. This charging process is not instantaneous or linear as the strength of the charging current is at its maximum when the capacitors plates are uncharged, decreasing exponentially over time until the capacitor is fully-charged.

This is because the electrostaic field between the plates opposes any changes to the potential difference across the plates at a rate that is equal to the rate of change of the electrical charge on the plates. The property of a capacitor to store a charge on its plates is called its capacitance, (C).

Thus a capacitors charging current can be defined as: i = CdV/dt. Once the capacitor is "fully-charged" the capacitor blocks the flow of any more electrons onto its plates as they have become saturated. However, if we apply an alternating current or AC supply, the capacitor will alternately charge and discharge at a rate determined by the frequency of the supply. Then the **Capacitance in AC circuits** varies with frequency as the capacitor is being constantly charged and discharged.

We know that the flow of electrons onto the plates of a capacitor is directly proportional to the rate of change of the voltage across those plates. Then, we can see that capacitors in AC circuits like to pass current when the voltage across its plates is constantly changing with respect to time such as in AC signals, but it does not like to pass current when the applied voltage is of a constant value such as in DC signals. Consider the circuit below.

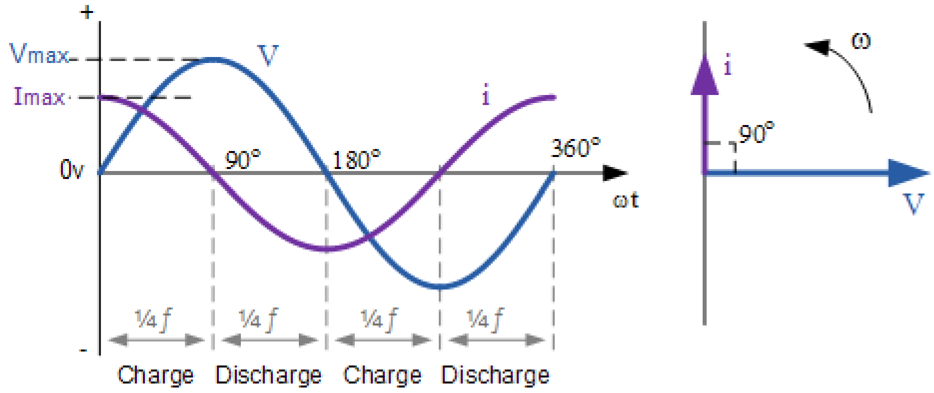
AC Capacitor Circuit



In the purely capacitive circuit above, the capacitor is connected directly across the AC supply voltage. As the supply voltage increases and decreases, the capacitor charges and discharges with respect to this change. We know that the charging current is directly proportional to the rate of change of the voltage across the plates with this rate of change at its greatest as the supply voltage crosses over from its positive half cycle to its negative half cycle or vice versa at points, 0^o and 180^o along the sine wave.

Consequently, the least voltage rate-of-change occurs when the AC sine wave crosses over at its maximum positive peak ($+V_{MAX}$) and its minimum negative peak, ($-V_{MAX}$). At these two positions within the cycle, the sinusoidal voltage is constant, therefore its rate-of-change is zero, so dv/dt is zero, resulting in zero current change within the capacitor. Thus when dv/dt = 0, the capacitor acts as an open circuit, so i = 0 and this is shown below.

AC Capacitor Phasor Diagram



At 0^o the rate of change of the supply voltage is increasing in a positive direction resulting in a maximum charging current at that instant in time. As the applied voltage reaches its maximum peak value at 90^o for a very brief instant in time the supply voltage is neither increasing or decreasing so there is no current flowing through the circuit.

As the applied voltage begins to decrease to zero at 180^o, the slope of the voltage is negative so the capacitor discharges in the negative direction. At the 180^o point along the line the rate of change of the voltage is at its maximum again so maximum current flows at that instant and so on.

Then we can say that for capacitors in AC circuits the instantaneous current is at its minimum or zero whenever the applied voltage is at its maximum and likewise the instantaneous value of the current is at its maximum or peak value when the applied voltage is at its minimum or zero.

From the waveform above, we can see that the current is leading the voltage by 1/4 cycle or 90^o as shown by the vector diagram. Then we can say that in a purely capacitive circuit the alternating voltage **lags** the current by 90^o.

We know that the current flowing through the capacitance in AC circuits is in opposition to the rate of change of the applied voltage but just like resistors, capacitors also offer some form of resistance against the flow of current through the circuit, but with capacitors in AC circuits this AC resistance is known as **Reactance** or more commonly in capacitor circuits, **Capacitive Reactance**, so capacitance in AC circuits suffers from **Capacitive Reactance**.

Capacitive Reactance

Capacitive Reactance in a purely capacitive circuit is the opposition to current flow in AC circuits only. Like resistance, reactance is also measured in Ohm's but is given the symbol X to distinguish it from a purely resistive value. As reactance is a quantity that can also be applied to Inductors as well as Capacitors, when used with capacitors it is more commonly known as **Capacitive Reactance**.

For capacitors in AC circuits, capacitive reactance is given the symbol Xc. Then we can actually say that **Capacitive Reactance** is a capacitors resistive value that varies with frequency. Also, capacitive reactance depends on the capacitance of the capacitor in Farads as well as the frequency of the AC waveform and the formula used to define capacitive reactance is given as:

Capacitive Reactance

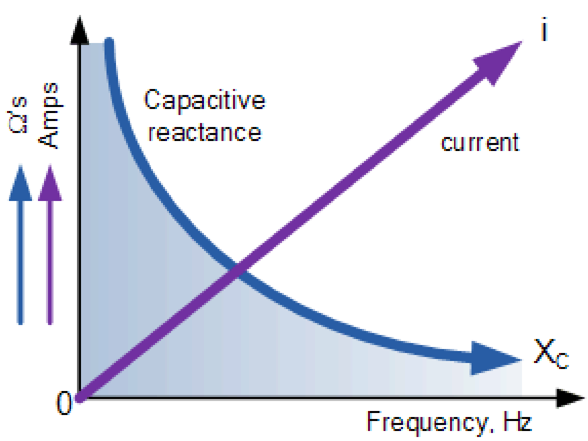
$$X_C = \frac{1}{2\pi f C} = \frac{1}{\omega C}$$

Where: F is in Hertz and C is in Farads. $2\pi f$ can also be expressed collectively as the Greek letter **Omega**, ω to denote an angular frequency.

From the capacitive reactance formula above, it can be seen that if either of the **Frequency** or **Capacitance** where to be increased the overall capacitive reactance would decrease. As the frequency approaches infinity the capacitors reactance would reduce to zero acting like a perfect conductor.

However, as the frequency approaches zero or DC, the capacitors reactance would increase up to infinity, acting like a very large resistance. This means then that capacitive reactance is "**Inversely proportional**" to frequency for any given value of Capacitance and this shown below:

Capacitive Reactance against Frequency



The capacitive reactance of the capacitor decreases as the frequency across it increases therefore capacitive reactance is inversely proportional to frequency.

The opposition to current flow, the electrostatic charge on the plates (its AC capacitance value) remains constant as it becomes easier for the capacitor to fully absorb the change in charge on its plates during each half cycle.

Also as the frequency increases the current flowing through the capacitor increases in value because the rate of voltage change across its plates increases.

Then we can see that at DC a capacitor has infinite reactance (open-circuit), at very high frequencies a capacitor has zero reactance (short-circuit).

AC Capacitance Example No1

Find the rms current flowing in an AC capacitive circuit when a 4μF capacitor is connected across a 880V, 60Hz supply.

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 60 \times (4 \times 10^{-6})} = 663\Omega$$

$$I_{RMS} = \frac{V_{RMS}}{X_C} = \frac{880V}{663\Omega} = 1.33\text{Amperes}$$

In AC circuits, the sinusoidal current through a capacitor, which leads the voltage by 90^o, varies with frequency as the capacitor is being constantly charged and discharged by the applied voltage. The AC impedance of a capacitor is known as **Reactance** and as we are dealing with capacitor circuits, more commonly called **Capacitive Reactance**, X_C

AC Capacitance Example No2.

When a parallel plate capacitor was connected to a 60Hz AC supply, it was found to have a reactance of 390 ohms. Calculate the value of the capacitor in micro-farads.

$$X_C = \frac{1}{2\pi f C} \quad \therefore C = \frac{1}{2\pi f X_C}$$

$$C = \frac{1}{2\pi \times 60 \times 390} = 6.8\text{uF}$$

This capacitive reactance is inversely proportional to frequency and produces the opposition to current flow around a capacitive AC circuit as we looked at in the AC Capacitance tutorial in the AC Theory section.

https://www.electronics-tutorials.ws/capacitor/capacitive-voltage-divider.html

Capacitive Voltage Divider

Voltage divider circuits may be constructed from reactive components just as easily as they may be constructed from fixed value resistors.

But just like resistive circuits, a capacitive voltage divider network is not affected by changes in the supply frequency even though they use capacitors, which are reactive elements, as each capacitor in the series chain is affected equally by changes in supply frequency.

But before we can look at a **capacitive voltage divider circuit** in more detail, we need to understand a little more about capacitive reactance and how it affects capacitors at different frequencies.

In our first tutorial about Capacitors, we saw that a capacitor consists of two parallel conductive plates separated by an insulator, and has a positive (**+**) charge on one plate, and an opposite negative (**-**) charge on the other. We also saw that when connected to a DC (direct current) supply, once the capacitor is fully charged, the insulator (called the dielectric) blocks the flow of current through it.

A capacitor opposes current flow just like a resistor, but unlike a resistor which dissipates its unwanted energy in the form of heat, a capacitor stores energy on its plates when it charges and releases or gives back the energy into the connected circuit when it discharges.

Typical Capacitor

This ability of a capacitor to oppose or “react” against current flow by storing charge on its plates is called “reactance”, and as this reactance relates to a capacitor it is therefore called **Capacitive Reactance** (Xc), and like resistance, reactance is also measured in Ohm’s.

When a fully discharged capacitor is connected across a DC supply such as a battery or power supply, the reactance of the capacitor is initially extremely low and maximum circuit current flows through the capacitor for a very short period time as the capacitors plates charge up exponentially.

After a period of time equal to about “5RC” or 5 time constants, the plates of the capacitor are fully charged equalling the supply voltage and no further current flows. At this point the reactance of the capacitor to DC current flow is at its maximum in the mega-ohms region, almost an open-circuit, and this is why capacitors block DC.

Now if we connect the capacitor to an AC (alternating current) supply which is continually reversing polarity, the effect on the capacitor is that its plates are continuously charging and discharging in relationship to the applied alternating supply voltage. This means that a charging and discharging current is always flowing in and out of the capacitors plates, and if we have a current flow we must also have a value of reactance to oppose it. But what value would it be and what factors determine the value of capacitive reactance.

In the tutorial about Capacitance and Charge, we saw that the amount of charge, (Q) present on a capacitors plates is proportional to the applied voltage and capacitance value of the capacitor. As the applied alternating supply voltage, (Vs) is constantly changing in value the charge on the plates must also be changing in value.

If the capacitor has a larger capacitance value, then for a given resistance, R it takes longer to charge the capacitor as $\tau = RC$, which means that the charging current is flowing for a longer period of time. A higher capacitance results in a small value of reactance, Xc for a given frequency.

Likewise, if the capacitor has a small capacitance value, then a shorter RC time constant is required to charge the capacitor which means that the current will flow for a shorter period of time. A smaller capacitance results in a higher value of reactance, Xc. Then we can see that larger currents mean smaller reactance, and smaller currents mean larger reactance. Therefore, capacitive reactance is inversely proportional to the capacitance value of the capacitor, $X_C \propto^{-1} C$.

Capacitance, however is not the only factor that determines capacitive reactance. If the applied alternating current is at a low frequency, the reactance has more time to build-up for a given RC time constant and oppose the current indicating a large value of reactance. Likewise, if the applied frequency is high, there is little time between the charging and discharging cycles for the reactance to build-up and oppose the current resulting in a larger current flow, indicating a smaller reactance.

Then we can see that a capacitor is an impedance and the magnitude of this impedance is frequency dependent. So larger frequencies mean smaller reactance, and smaller frequencies mean larger reactance. Therefore, **Capacitive Reactance**, Xc (its complex impedance) is inversely proportional to both capacitance and frequency and the standard equation for capacitive reactance is given as:

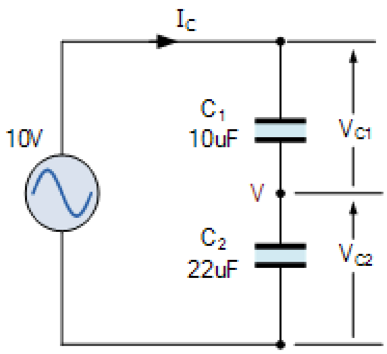
Capacitive Reactance Formula

$$Xc = \frac{1}{2\pi f C}$$

- Where:
- Xc = Capacitive Reactance in Ohms, (Ω)
- π (pi) = a numeric constant of 3.142
- f = Frequency in Hertz, (Hz)
- C = Capacitance in Farads, (F)

Voltage Distribution in Series Capacitors

Now that we have seen how the opposition to the charging and discharging currents of a capacitor are determined not only by its capacitance value but also by the frequency of the supply, lets look at how this affects two capacitors connected in series forming a capacitive voltage divider circuit.



Capacitive Voltage Divider

Consider the two capacitors, C1 and C2 connected in series across an alternating supply of 10 volts. As the two capacitors are in series, the charge Q on them is the same, but the voltage across them will be different and related to their capacitance values, as V = Q/C.

Voltage divider circuits may be constructed from reactive components just as easily as they may be constructed from resistors as they both follow the voltage divider rule. Take this capacitive voltage divider circuit, for instance.

The voltage across each capacitor can be calculated in a number of ways. One such way is to find the capacitive reactance value of each capacitor, the total circuit impedance, the circuit current and then use them to calculate the voltage drop, for example:

Capacitive Voltage Divider Example No1

Using the two capacitors of 10uF and 22uF in the series circuit above, calculate the rms voltage drops across each capacitor when subjected to a sinusoidal voltage of 10 volts rms at 80Hz.

Capacitive Reactance of 10uF capacitor

$$X_{C1} = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 80 \times 10 \times 10^{-6}} = 200\Omega$$

Capacitive Reactance of 22uF capacitor

$$X_{C2} = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 80 \times 22 \times 10^{-6}} = 90\Omega$$

Total capacitive reactance of series circuit – Note that reactance’s in series are added together just like resistors in series.

$$Xc_{(total)} = X_{C1} + X_{C2}$$
$$= 200\Omega + 90\Omega = 290\Omega$$

or:

$$C_T = \frac{C_1 \times C_2}{C_1 + C_2} = \frac{10uF \times 22uF}{10uF + 22uF} = 6.88uF$$

$$X_C = \frac{1}{2\pi f C_T} = \frac{1}{2\pi \times 80 \times 6.88uF} = 290\Omega$$

Circuit current

$$I = \frac{E}{Xc} = \frac{10V}{290\Omega} = 34.5mA$$

Then the voltage drop across each capacitor in series capacitive voltage divider will be:

$$V_{C1} = I \times X_{C1} = 34.5mA \times 200\Omega = 6.9V$$

$$V_{C2} = I \times X_{C2} = 34.5mA \times 90\Omega = 3.1V$$

When the capacitor values are different, the smaller value capacitor will charge itself to a higher voltage than the larger value capacitor, and in our example above this was 6.9 and 3.1 volts respectively. Since Kirchhoff's voltage law applies to this and every series connected circuit, the total sum of the individual voltage drops will be equal in value to the supply voltage, V_S and 6.9 + 3.1 does indeed equal 10 volts.

Note that the ratios of the voltage drops across the two capacitors connected in a series capacitive voltage divider circuit will always remain the same regardless of the supply frequency. Then the two voltage drops of 6.9 volts and 3.1 volts above in our simple example will remain the same even if the supply frequency is increased from 80Hz to 8000Hz as shown.

Capacitive Voltage Divider Example No2

Using the same two capacitors, calculate the capacitive voltage drop at 8,000Hz (8kHz).

$$X_{C1} = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 8000 \times 10uF} = 2\Omega$$

$$X_{C1} = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 8000 \times 22uF} = 0.9\Omega$$

$$I = \frac{V}{X_{C(Total)}} = \frac{10}{2.9} = 3.45\,\text{Amps}$$

$$\therefore V_{C1} = I \times X_{C1} = 3.45A \times 2\Omega = 6.9V$$

and

$$V_{C2} = I \times X_{C2} = 3.45A \times 0.9\Omega = 3.1V$$

While the voltage ratios across the two capacitors may stay the same, as the supply frequency increases, the combined capacitive reactance decreases, and therefore so too does the total circuit impedance. This reduction in impedance causes more current to flow. For example, at 80Hz we calculated the circuit current above to be about 34.5mA, but at 8kHz, the supply current increased to 3.45A, 100 times more. Therefore, the current flowing through a capacitive voltage divider is proportional to frequency or $I \propto f$.

We have seen here that a capacitor divider is a network of series connected capacitors, each having a AC voltage drop across it. As capacitive voltage dividers use the capacitive reactance value of a capacitor to determine the actual voltage drop, they can only be used on frequency driven supplies and as such do not work as DC voltage dividers. This is mainly due to the fact that capacitors block DC and therefore no current flows.

Capacitive voltage divider circuits are used in a variety of electronics applications ranging from Colpitts Oscillators, to capacitive touch sensitive screens that change their output voltage when touched by a persons finger, to being used as a cheap substitute for mains transformers in dropping high voltages such as in mains connected circuits that use low voltage electronics or IC’s etc.

Because as we now know, the reactance of both capacitors changes with frequency (at the same rate), so the voltage division across a capacitive voltage divider circuit will always remain the same keeping a steady voltage divider.

https://www.electronics-tutorials.ws/capacitor/cap_9.html

Capacitor Tutorial Summary

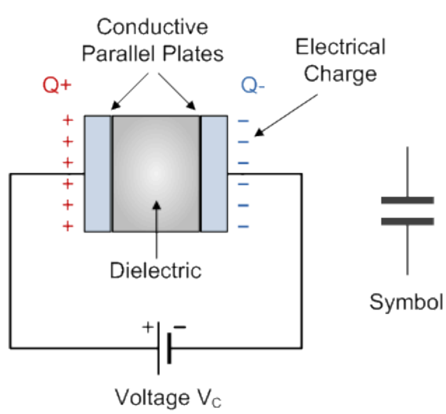
A capacitor consists of two metal plates separated by a dielectric.

Capacitors are energy storage devices which have the ability to store an electrical charge across its plates. Thus capacitors store energy as a result of their ability to store charge and an ideal capacitor would not loose its stored energy.

The simplest construction of a capacitor is by using two parallel conducting metal plates separated through a distance by an insulating material, called a the dielectric as summarised below.

- A capacitor consists of two metal plates separated by a dielectric.
- The dielectric can be made of many insulating materials such as air, glass, paper, plastic etc.
- A capacitor is capable of storing electrical charge and energy.
- The higher the value of capacitance, the more charge the capacitor can store.
- The larger the area of the plates or the smaller their separation the more charge the capacitor can store.
- A capacitor is said to be “Fully Charged” when the voltage across its plates equals the supply voltage.
- The symbol for electrical charge is Q and its unit is the Coulomb.
- Electrolytic capacitors are polarized. They have a +ve and a -ve terminal.
- Capacitance is measured in **Farads**, which is a very large unit so **micro-Farad** (μF), **nano-Farad** (nF) and **pico-Farad** (pF) are generally used.
- Capacitors that are daisy chained together in a line are said to be connected in **Series**.
- Capacitors that have both of their respective terminals connected to each terminal of another capacitor are said to be connected in **Parallel**.
- Parallel connected capacitors have a common supply voltage across them.
- Series connected capacitors have a common current flowing through them.
- Capacitive reactance, X_C is the opposition to current flow in AC circuits.
- In AC capacitive circuits the voltage “lags” the current by 90^o.

The basic construction and symbol for a parallel plate capacitor is given as:



https://www.electronics-tutorials.ws/capacitor/ultracapacitors.html

Ultracapacitors

Ultracapacitors are electrical energy storage devices that have the ability to store a large amount of electrical charge.

Unlike the resistor, which dissipates energy in the form of heat, the ideal capacitor does not loose its energy. We have also seen that the simplest form of a capacitor is two parallel conducting metal plates which are separated by an insulating material, such as air, mica, paper, ceramic, etc, and called the dielectric through a distance, “d”.

A typical Ultracapacitor

Capacitors store energy as a result of their ability to store charge with the amount of charge stored on a capacitor depending on the voltage, V applied across its plates, and the greater the voltage, the more charge will be stored by the capacitor as: Q ∞ V.

A capacitor has a constant of proportionality, called capacitance, symbol C, which represents the capacitor’s ability or capacity to store an electrical charge with the amount of charge depending on a capacitor capacitance value as: Q ∞ C.

Then we can see that there is a relationship between the charge, Q, voltage V and capacitance C, and the larger the capacitance, the higher is the amount of charge stored on a capacitor for the same amount of voltage and we can define this relationship for a capacitor as being:

Charge on a Capacitor

$$Q = C \times V$$

Where: Q (Charge, in Coulombs) = C (Capacitance, in Farads) times V (Voltage, in Volts)

The unit of capacitance is the coulomb/volt, which is also called the Farad (F) [named after M. Faraday] with one farad being defined as the capacitance of a capacitor, which requires a charge of 1 coulomb to establish a potential difference of 1 volt between its two plates.

But a conventional one farad capacitor would be very large for most practical electronic applications, hence much smaller units like the microfarad (μF), nanofarad (nF) and picofarad (pF) are commonly used where:

- Microfarad (μF) 1μF = 1/1,000,000 = 0.000001 = 10^{-6} F
- Nanofarad (nF) 1nF = 1/1,000,000,000 = 0.000000001 = 10^{-9} F
- Picofarad (pF) 1pF = 1/1,000,000,000,000 = 0.000000000001 = 10^{-12} F

However, there is another type of capacitor available, called an **Ultracapacitor** or **Supercapacitor** which can provide values from a few milli-farads (mF) to ten’s of farads of capacitance in a very small size allowing for much more electrical energy to be stored between their plates.

In our tutorial about Capacitance and Charge we saw that the energy stored in a capacitor is given by the equation:

$$E = \frac{1}{2}CV^2 \text{ in Joules}$$

Where: E is the energy stored in the electric field in joules, V is the potential difference across the plates and C is the capacitance of the capacitor in farads and defined as:

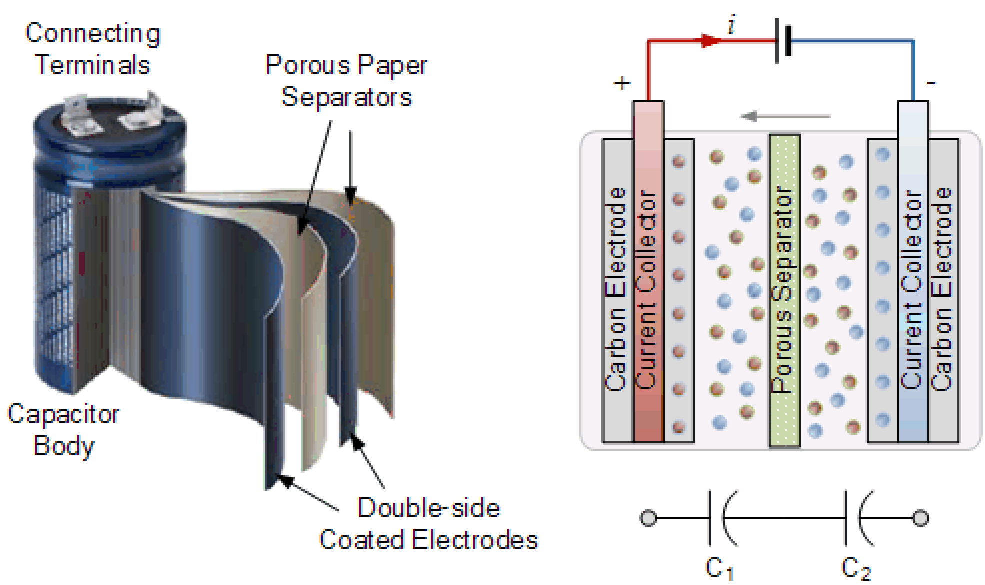
$$C = \varepsilon\frac{A}{d} \text{ in Farads}$$

Where: ε is the permittivity of the material between the plates, A is the area of the plates, and d is the separation of the plates.

Ultracapacitors are another type of capacitor which is constructed to have a large conductive plate, called an electrode, surface area (A) as well as a very small distance (d) between them. Unlike conventional capacitors that use a solid and dry dielectric material such as Teflon, Polyethylene, Paper, etc, the ultracapacitor uses a liquid or wet electrolyte between its electrodes making it more of an electrochemical device similar to an electrolytic capacitor.

Although an ultracapacitor is a type of electrochemical device, no chemical reactions are involved in the storing of its electrical energy. This means that the ultra-capacitor remains effectively an electrostatic device storing its electrical energy in the form of an electric field between its two conducting electrodes as shown.

Ultracapacitor Construction



The double sided coated electrodes are made from graphite carbon in the form of activated conductive carbon, carbon nanotubes or carbon gels. A porous paper membrane called a separator keeps the electrodes apart but allows positive ion to pass through while blocking the larger electrons. Both the paper separator and carbon electrodes are impregnated with the liquid electrolyte with an aluminium foil used in between the two to act as the current collector making electrical connection to the ultracapacitors solder tabs.

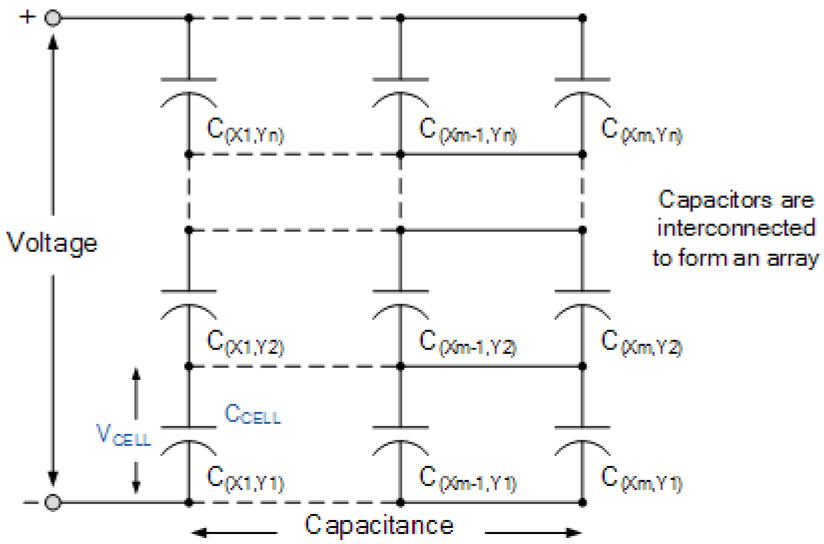
The double layer construction of the carbon electrodes and separator may be very thin but their effective surface area into the thousands of meters squared when coiled up together. Then in order to increase the capacitance of an ultra-capacitor, it is obvious that we need to increase the contact surface area, A (in m^2) without increasing the capacitors physical size, or use a special type of electrolyte to increase the available positive ions to increase conductivity.

Then **ultra-capacitors** make excellent energy storage devices because of their high values of capacitance up into the hundreds of farads, due to the very small distance d or separation of their plates and the electrodes high surface area A for the formation on the surface of a layer of electrolytic ions forming a double layer. This construction effectively creates two capacitors, one at each carbon electrode, giving the ultracapacitor the secondary name of “double layer capacitor” forming two capacitors in series.

However, the problem with this small size is that the voltage across the capacitor can only be very low as the rated voltage of the ultra-capacitor cell is determined mainly by the decomposition voltage of the electrolyte. Then a typical capacitor cell has a working voltage of between 1 to 3 volts, depending on the electrolyte used, which can limit the amount of electrical energy it can store.

In order to store charge at a reasonable voltage ultracapacitors have to be connected in series. Unlike electrolytic and electrostatic capacitors, ultra-capacitors are characterized by there low terminal voltage. In order to increase there rated terminal voltage to tens of volts, ultracapacitor cells must be connected in series, or in parallel to achieve higher capacitance values as shown.

Increasing An Ultracapacitors Value



Where: V_{CELL} is the voltage of one cell, and C_{CELL} is the capacitance of one cell.

As the voltage of each capacitor cell is about 3.0 volts, connecting more capacitor cells together in series will increase the voltage. While connecting more capacitor cells in parallel will increase its capacitance. Then we can define the total voltage and total capacitance of a ultracapacitor bank as:

$$\text{Voltage, } V = V_{CELL} \times N$$

$$\text{Capacitance, } C = C_{CELL} \times \left[\frac{M}{N} \right]$$

Where: M is the number of columns and N is the number of rows. Note also that like batteries, ultracapacitor and supercapacitors have a defined polarity with the positive terminal marked on the capacitor body.

Ultracapacitor Example No1

A 5.5 volt, 1.5 farad ultracapacitor is required as an energy storage backup device for an electronic circuit. If the ultracapacitor is to be made from individual 2.75v, 0.5F cells, calculate the number of cells required and the layout of the array.

$$V = V_{CELL} \times N$$

$$\therefore N = \frac{V}{V_{CELL}} = \frac{5.5}{2.75} = 2$$

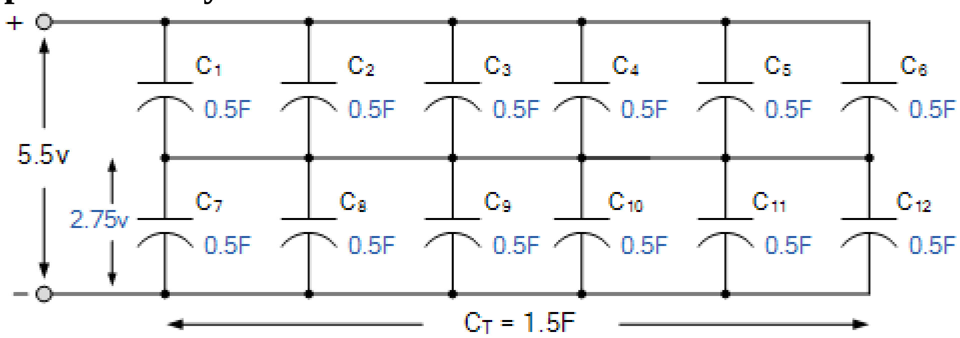
The array will therefore have two capacitor cells of 2.75v each connected in series to provide the required 5.5v.

$$C = C_{CELL} \times \left[\frac{M}{N}\right]$$

$$\therefore M = \frac{C \times N}{C_{CELL}} = \frac{1.5 \times 2}{0.5} = 6$$

Then the array will have a total of six individual columns, consisting of two rows of six thereby forming an ultracapacitor with a 6 x 2 array as shown.

6×2 Ultracapacitor Array



Ultracapacitor Energy

As with all capacitors, an ultracapacitor is a energy storage device. Electrical energy is stored as charge in the electric field between its plates and as a result of this stored energy, a potential difference, that is a voltage, exists between the two plates. During charging (current flowing through the ultracapacitor from the connected supply), electrical energy is stored between its plates.

Once the ultracapacitor is charged, current stops flowing from the supply and the ultracapacitors terminal voltage is equal to the voltage of the supply. As a result, a charged ultracapacitor will store this electrical energy even when removed from the voltage supply until it is needed acting as an energy storage device.

When discharging (current flowing out), the ultracapacitor changes this stored energy into electrical energy to supply the connected load. Then an ultracapacitor does not consume any energy itself but instead will store and release electrical energy as required with the amount of energy stored in the ultracapacitor being in proportion to the capacitance value of the capacitor.

As previously mentioned, the amount of energy stored is proportional to the capacitance C and the square of the voltage V across its terminals giving.

$$E = \frac{1}{2}CV^2 = \frac{CV^2}{2} = \frac{QV}{2} = \frac{Q^2}{2C} \text{ Joules}$$

Where: E is the energy stored in joules. Then for our ultracapacitor example above, the amount of energy stored by the array is given as:

$$E = \frac{1}{2}CV^2 = \frac{1.5 \times 5.5^2}{2} = 22.7 \text{ Joules}$$

Then the maximum amount of energy that can be stored by our ultracapacitor is 22.7 joules, which was originally supplied by the 5.5 volt charging supply. This stored energy remains available as charge in the electrolyte dielectric and when connected to a load, the ultracapacitors entire 22.69 joules of energy is made available as an electric current. Obviously, when the ultracapacitor is fully discharged, the stored energy is zero.

Then we can see that an ideal ultracapacitor would not consume or dissipate energy, but instead take power from an external charging circuit to store energy in its electrolyte field and then return this stored energy when delivering power to a load.

In our simple example above, the energy stored by the ultracapacitor was about 23 joules, but with large capacitance values and higher voltage ratings, the energy density of ultracapacitors can be very large making them ideal as energy storage devices.

In fact, ultracapacitors with ratings into the thousands of farads and hundreds of volts are now being used in hybrid electric vehicles (including Formula 1) as solid state energy storage devices for regenerative braking systems as they can quickly giving out and receiving energy during braking and accelerating afterwards. Ultra and super-capacitors are also used in renewable energy systems to replace lead acid batteries.

Ultracapacitor Summary

We have seen that an *ultracapacitor* is an electrochemical device consisting of two porous electrodes, usually made up of activated carbon immersed in an electrolyte solution that stores charge electrostatically. This arrangement effectively creates two capacitors, one at each carbon electrode, connected in series.

The ultracapacitor is available with capacitances in the hundreds of farads all within a very small physical size and can achieve much higher power density than batteries. However, the voltage rating of an ultracapacitor is usually less than about 3 volts so several capacitors have to be connected in series and parallel combinations to provide any useful voltage.

Ultracapacitors can be used as energy storage devices similar to a battery, and in fact are classed as an ultracapacitor battery. But unlike a battery, ultracapacitors can achieve much higher power densities over a shorter time duration.

Also, ultracapacitors are now used in many hybrid petrol vehicles as well as fuel cell driven electric vehicles due to their ability to discharge high voltages quickly and then be recharged once again ready for the next cycle.

By using ultracapacitors along with conventional fuel cells and automotive batteries, peak power demands and transient variations in load conditions can be controlled much more efectively.