What is Capacitance: basic concepts

Capacitance is one of the basic concepts behind electronics, and it is widely used, as seen by the number of capacitors that are used in electronic circuits

Capacitance Tutorial Includes:

Capacitance Capacitor formulas Capacitive reactance Parallel & series capacitors Dielectric constant & relative permittivity Dissipation factor, loss tangent, ESR Capacitor conversion chart

Resistance, capacitance and inductance are three basic parameters associated with electrical and electronic circuits.

Unlike the other two, capacitance is associated with the storage of electrical charge and the attributes are used in electronic components called capacitors and in turn these are used in many electrical circuits and virtually every electronic circuit design.

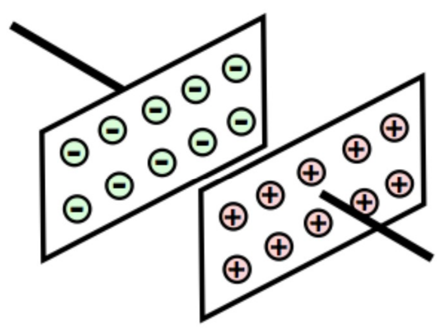
The effects of capacitance can be used in a variety of ways in circuits ranging from electrical motors to electronic circuit designs like power supplies, audio circuits, RF circuits, logic and digital circuits and very many more.

In view of this, capacitance is a particularly important parameter which is used in many areas.

What is capacitance

When looking at capacitance, it is first necessary to look at exactly what it is. Capacitance is effectively the ability to store charge. In its simplest form a capacitor consists of two parallel plates. It is found that when a battery or any other voltage source is connected to the two plates as shown a current flows for a short time and one plate receives an excess of electrons, while the other has too few.

In this way one plate, the one with the excess of electrons becomes negatively charge, while the other becomes positively charged.



Charge stored on two plates of a capacitor

If the battery is removed the capacitor will retain its charge. However if a resistor is placed across the plates, a current will flow until the capacitor becomes discharged.

Accordingly it is possible to define what capacitance is:

Capacitance definition:

Capacitance is the ability of a component or circuit to collect and store energy in the form of an electrical charge. It is the amount of electric charge stored on a conductor for a stated difference in electric potential.

The larger the plates, the more charge can be stored, and also the closer they are together, the more charge they store. The charge storage is also dependent upon the material between the two plates as well.

Units or capacitance

It is necessary to be able to define the "size" of a capacitor. The capacitance of a capacitor is a measure of its ability to store charge, and the basic unit of capacitance is the Farad, named after Michael Faraday.

It is worth defining the Farad which is the basic unit of capacitance.

Capacitance: Farad definition:

A capacitor has a capacitance of one Farad when a potential difference of one volt will charge it with one coulomb of electricity (i.e. one Amp for one second).

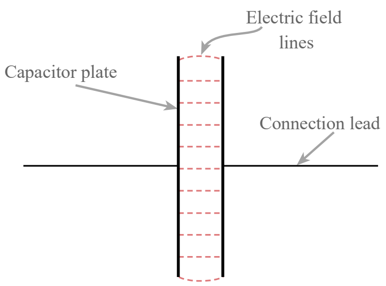
A capacitor with a capacitance of one Farad is too large for most electronics applications, and components with much smaller values of capacitance are normally used. Three prefixes (multipliers) are used, µ (micro), n (nano) and p (pico):

CAPACITANCE UNITS PREFIXES AND MULTIPLIERS

PREFIX	MULTIPLIER	TERMINOLOGY
µ	10^{-6} (millionth)	1000000µF = 1F
n	10^{-9} (thousand-millionth)	1000nF = 1µF
p	10^{-12} (million-millionth)	1000pF = 1nF

Electric fields and dielectrics

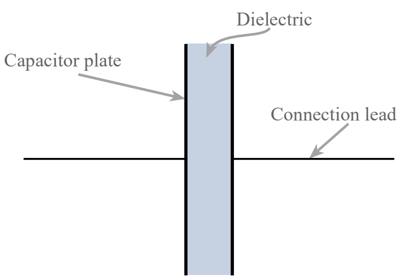
As there is a potential across the plates of a capacitor, there is an associate electric field present. With parallel plates, the electric field lines are generally parallel to each other and at right angles to the plates.



Capacitor plates showing electric field lines

Capacitors require some form of insulator between the two plates, otherwise the charge could not remain on the plates, it would dissipate through the medium between the two plates.

Whilst air is a good insulator, often the capacitor plates need to be kept apart by some form of rigid insulator.



Simplified view of construction of capacitor showing the plates and insulating dielectric

The material between the two plates is called the dielectric. This not only acts as an insulator, but it also determines many of the other properties. A measure known as the dielectric constant affects the level of capacitance achievable for a given capacitor plate size and spacing.

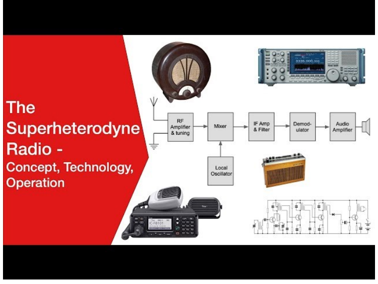
High levels of relative permittivity / dielectric constant can increase the capacitance many times.

The topic of relative permittivity and dielectric constant, etc, is a topic in its own right, and although easy to comprehend, possibly needs to be looked at separately.

Read more about . . . . ***Relative permittivity & dielectric constant.***

Capacitor charging and discharging

It is also possible to look at the voltage across the capacitor as well as looking at the charge. After all it is easier to measure the voltage on it using a simple meter. When the capacitor is discharged there is no voltage across it. Similarly, one it is fully charged no current is flowing from the voltage source and therefore it has the same voltage across it as the source.



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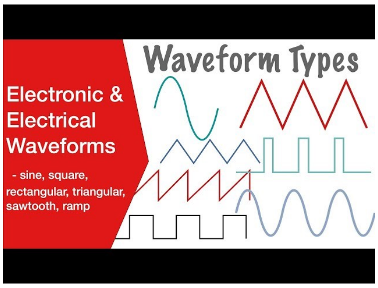

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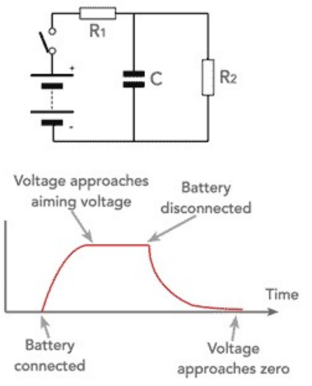
In an ideal circuit with no stray resistance or inductance, when a voltage is applied to a capacitor, it would instantly charge up and the voltage across it would be the same as that of the source of the electric potential.

In reality there will always be some resistance in the circuit, and therefore the capacitor will be connected to the voltage source through a resistor. This means that it will take a finite time for the capacitor to charge up, and the rise in voltage does not take place instantly.

It is found that the rate at which the voltage rises is much faster at first than after it has been charging for some while. Eventually it reaches a point when it is virtually fully charged and almost no current flows.

In theory the capacitor never becomes fully charged as the curve is asymptotic. However in reality it reaches a point where it can be considered to be fully charged or discharged and no current flows.



Voltage of capacitor as it charges and discharges

Similarly the capacitor will always discharge through a resistance. As the charge on the capacitor falls, so the voltage across the plates is reduced. This means that the current will be reduced, and in turn the rate at which the charge is reduced falls.

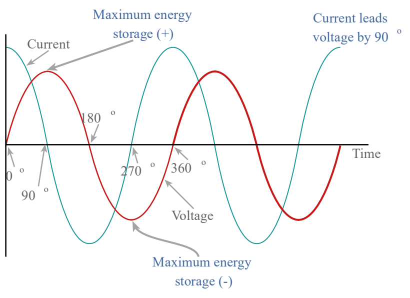
This means that the voltage across the capacitor falls in an exponential fashion, gradually approaching zero.

The rate at which the voltage rises or decays is dependent upon the resistance in the circuit. The greater the resistance the smaller the amount of charge which is transferred and the longer it takes for the capacitor to charge or discharge.

Application of alternating waveform to a capacitor

So far the case when a battery has been connected to charge the capacitor and disconnected and a resistor applied to charge it up have been considered. If an alternating waveform, which by its nature is continually changing is applied to the capacitor, then it will be in a continual state of charging and discharging.

For this to happen a current must be flowing in the circuit. In this way a capacitor will allow an alternating current to flow, but it will block a direct current. As such capacitors are used for coupling an AC signal between two circuits which are at different steady state potentials.



Current and voltage waveforms for a perfect capacitor
Note: the current leads the voltage waveform by 90°.

It is found that when the sine-wave is first applied first applied, the rate of change of the voltage is at its greatest and this means that the charge is increasing at its fastest rate and hence the current flowing into the capacitor will be at its greatest. In other words the current is at its maximum.

As the voltage on the capacitor increases, the rate of change of voltage decreases and as a result the increase in charge and hence the current falls. Eventually the peak of the voltage sine-eave is reached where there is no change in voltage and accordingly the current at this point is zero.

After the voltage peak, the voltage starts to decreases, and accordingly the level of charge falls and this means that current flows out of the capacitor from this point.

The remainder of the waveform follows in a similar fashion. As a result it can be seen that the voltage and current are not in phase with each other. The current lags the voltage by a quarter of a cycle, i.e. 90°.

It is possible to express the current and voltage relationship for a perfect capacitor as:

$$V_t = \sin(\omega t)$$

$$I_t = \sin(\omega t + 90)$$

Real capacitors

Capacitors are the electronic components that provide the capacitance required in electrical and electronic circuits.

Capacitors come in a wide variety of forms, each with its own properties. The physical capacitors may be either surface mount or the traditional leaded varieties as well as having different form factors and electrical performance properties.

Note on the Types of Capacitor:

There are many different types of capacitor that are available. Although capacitance is a universal measure, different capacitors have different characteristics in terms of elements like maximum current capability, frequency response, size, voltage, stability, tolerance and the like. To accommodate these parameters some capacitor types are better than others in some applications,

Read more about ***Capacitor Types.***

Selecting the right capacitor is not only a matter of choosing the right level of capacitance, but also many other aspects including the dielectric, size, levels of equivalent series resistance and many more items.

In view of all these requirements, there is a very wide selection of these electronic components available for use in electrical and electronic circuit designs, etc.

Capacitance is one of the main parameters associated with electrical and electronic science. Capacitance equations and calculations are used everyday in electronic circuit design and many other areas, and capacitance is not a measure that is only associated with capacitors, there can be levels of capacitance in many other electronic components including resistors, inductors, wires, printed circuit boards and many other items.

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Capacitor Formulas

key equations and calculations for capacitors and capacitance in electronics circuits including charge, value, . . .

Capacitance Tutorial Includes:
Capacitance Capacitor formulas Capacitive reactance Parallel & series capacitors Dielectric constant & relative permittivity Dissipation factor, loss tangent, ESR Capacitor conversion chart

There are many calculations and equations associated with capacitors. The capacitor reactance equations and calculations are common, but there are many more capacitor calculations that may need to be performed.

Capacitor equations and capacitor calculations include many aspects of capacitor operation including the capacitor charge, capacitor voltage capacitor reactance calculations and many more.

Basic capacitance formulae

The very basic capacitor equations link the capacitance with the charge held on the capacitor, and the voltage across the plates.

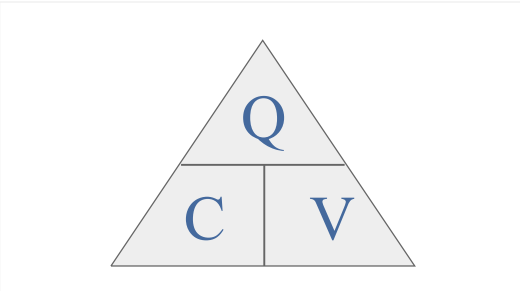
Capacitance is defined as the ability of an electrical or electronic component or circuit to collect and store energy in the form of an electrical charge. It is the amount of electric charge stored on a conductor for a stated difference in electric potential.

From this it is possible to define the basic equation for capacitance:

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

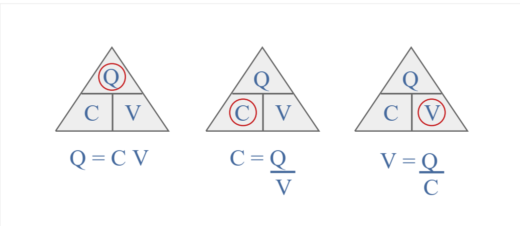
Where
C is the capacitance in Farads
Q is the charge held on the plates in coulombs
V is the potential difference across the plates in volts

It is useful to be able to remember the basic equation for capacitance. It is used in a number of electrical and electronic circuit design applications. To do this, it is helpful to use a memory triangle similar to that of the Ohm's law triangle, but using the capacitance variables instead.



It is very simple to use the capacitance calculation triangle. Simply cover up the unknown quantity and then and then calculate it from the other two. If they are in line they are multiplied, but if one is on top of the other then they should be divided.

For example if Q is required from a knowledge of C and V, then, because C and V are at the bottom of the triangle, and they are next to each other, then we can see that Q = C x V.< etc.



The summary above gives all the variations of the formula so that they can be remembered very easily.

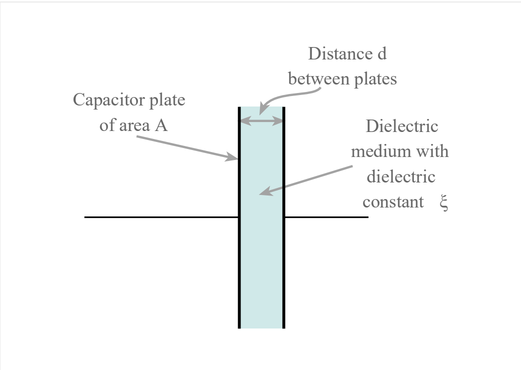
Calculation of capacitance or parallel plate capacitor

One of the important basic calculations associated with capacitance is to be able to calculate the capacitance of a parallel plate capacitor.

Using the relevant formulas it is possible to accurately predict the capacitance of a capacitor from a knowledge of the area of the plates, the separation between them and the relative permittivity of dielectric constant of the material between the two plates.

It is also possible to understand the stray capacitance levels on printed circuit boards and other aspects of electronic circuit design.

It is possible to deduce the capacitance of a capacitor from the equation below. The plates must be of the same size.

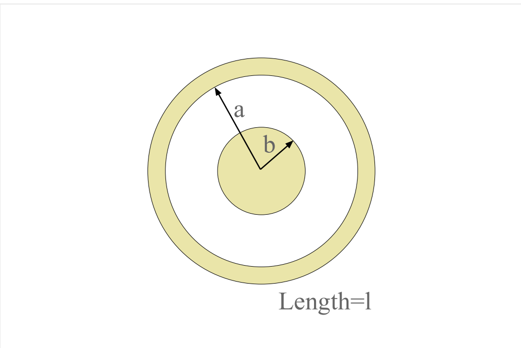


$$C = \varepsilon_r \ \varepsilon_0 \ \frac{A}{d}$$

Where:

C = capacitance in Farads
ε_r = relative permittivity for that medium
ε_0 = permittivity of space and it is equal to 8.854×10^{-12} F/m
A = the area of one plate in square metres
d = distance between the two plates in metres

Determining the capacitance for a plate capacitor is very useful for where ordinary flat capacitors are to be used. However it is sometimes necessary to be able to determine the capacitance for a tubular capacitor. One example of this is when it is necessary to determine the capacitance of a length of coaxial feeder.



This can easily be accomplished using a slightly modified version of the formula for the plate capacitor which has been adapted to accommodate the different geometry of the tubular capacitor.

$$C = \frac{2\pi \ \varepsilon_r \ \varepsilon_0 l}{\log\left(\frac{a}{b}\right)}$$

These are the most widely used instances where it is necessary to calculate the capacitance of an item. It is possible to derive the relevant formulas for other geometries, but they tend to be more individual and not widely used.

The dielectric constant and relative permittivity are used within these equations. Gain a greater understanding . . .

Read more about . . . . *Permittivity, relative permittivity & Dielectric Constant.*

Energy stored in a capacitor

Another important equation associated with capacitors is to determine the amount of energy stored in the capacitor.

The energy stored in the capacitor is equal tot he work that was required to pace the charge into the capacitor.

If the voltage at any instant is "v", and a small amount of charge δq is transferred at this voltage, then the work done will be v δq.

Hence the total work done, and accordingly the energy stored in the capacitor is:

$$W = \int_0^Q V \, dQ$$

From this we can see:

$$W = \int_0^Q \frac{q}{C} \, dQ$$

Accordingly:

$$W = \frac{1}{2} C V^2$$

The basic equations for capacitors and their capacitance enable the levels of capacitance to be calculated, along with the energy stored within them. These are some of the key basic formulas and attributes needed for basic capacitor theory.

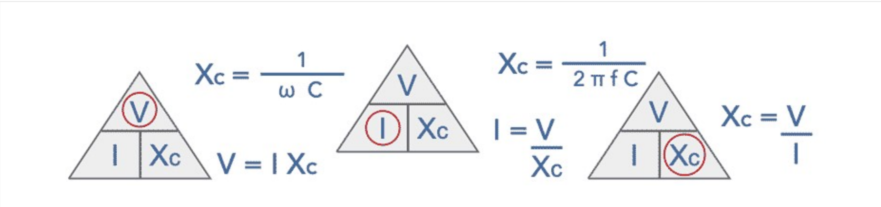
Capacitive reactance

The capacitive reactance is a measure of how a capacitor restricts the flow of alternating current, although similar to resistance, it is not the same.

We are familiar with the way resistors restrict the flow of electrical charge because of their resistance and Ohm's Law, but capacitors can also impede the flow of electrical charge with an alternating current as a result of their reactance.

It is important to know what effect a capacitor will have on any circuit in which it operates. Not only does it prevent the direct current component of a signal from passing through, but also has an effect on any alternating signal that may appear.

Being able to calculate the level of reactance is important because capacitors are used in many electrical and electronic circuit designs. Also knowing how this reactance affects the current flow with other electronic components is also of great importance.



What is capacitive reactance

In a direct current circuit where there may be a battery and a resistor, it is the resistor that resists the flow of current in the circuit. This is basic Ohms Law. The same is true for an alternating current circuit with a capacitor.

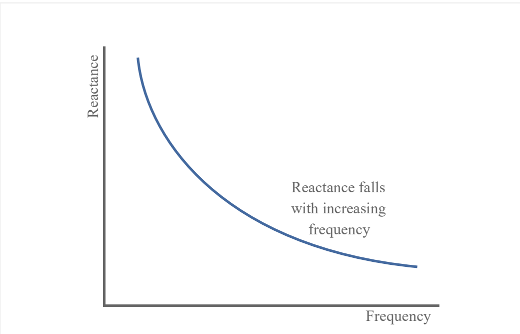
A capacitor with a small plate area will only be able to store a small amount of charge, and this will impede the flow of current. A larger capacitor will allow a greater flow of current.

In view of the differing levels of charge storage, it can be seen that if only a small level of charge can be stored, this will present a greater level of restriction on the current that can be passed by the capacitor than one that can store much more charge.

The 'restriction' on the current that can be passed by a capacitor is called the reactance of the capacitor.

The reactance of a capacitor is different to the resistance of a resistor, but it is nevertheless measured in Ohms just the same. The reactance of a capacitor is dependent upon the value of the capacitor and also the frequency of operation. The higher the frequency the smaller the reactance.

It is found that the greater the frequency the lower the reactance and a curve such as that shown below is seen for a capacitor of a given value.



Capacitive reactance vs frequency

Calculating the reactance of a capacitor

It can be imagined that the larger the capacitor, the more charge it can store and hence the less it will restrict current flow.

Also the frequency by which the current alternates has a major impact. If the frequency is higher, it means that there is a greater change in the stored charge and hence the restriction on current, i.e. reactance is less.

The basic equation for the reactance of a capacitor is:

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

Where
- X_c is the capacitive reactance in Ohms
- ω is the angular velocity in radians per second
- C is the capacitance in Farads

However it is normally far more useful to calculate the reactance with a knowledge of the frequency. Frequency in cycles per second or Hertz is far more widely used as a unit than the angular velocity.

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

Where
- X_c is the capacitive reactance in Ohms
- f is the frequency in Hertz
- C is the capacitance in Farads

As an example it is possible to calculate the reactance of a capacitor with a capacitance of 1 µF at a frequency of 1kHz.

Substituting directly into the equation, and using 2 π as 6 which is a sufficiently close approximation for most calculations.

$$X_c = \frac{1}{2\pi 10^3 10^{-6}}$$

This simplifies down to give:

$$X_c = 166\Omega$$

In this way it can be seen that it is very easy to calculate the reactance of a capacitor. The main point to watch is that all the frequencies and capacitances are measured in Hz and Farads. Keeping track of the zeros or power of ten multipliers in the figures is key to obtaining the right answer.

Current calculations

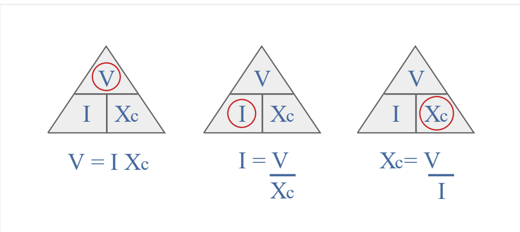
The next stage is to look at how the current, for example can be calculated for a capacitor such as the one above.

If the only component present is the capacitor, then it is simply a matter of applying Ohm's law and calculating the voltage or current, etc from a knowledge of the other two variables. It is also possible to calculate the reactance from a knowledge of the voltage and current.

$$V = I\ X_c$$

It is simply a matter of replacing 'R' in the Ohm's Law equation with X_c.

It is also possible to use the Ohm's law triangles to calculate the values of unknown variable.



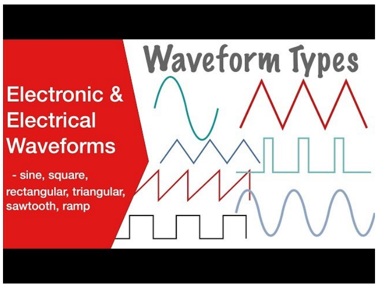
It can be seen that the resistance R normally seen int he Ohm's Law equation and the Ohm's law triangle has simply been replaced by the capacitive reactance X_c.

Adding resistance and reactance

Although resistance and reactance are very similar, and the values of both are measured in Ohms, they are not exactly the same. The current and voltage are 90° out of phase and whereas for a resistor they are in phase.

As a result it is not possible to add the resistor resistance and the capacitor reactance directly together.

Instead they have to be summed "vectorially". In other words it is necessary to square each value, and then add these together and take the square root of this figure. Put in a more mathematical format:



$$X_{\text{total}}^2 = X_c^2 + R^2$$

This can be expressed more conveniently for calculations as:

$$X_{\text{total}} = \sqrt{X_c^2 + R^2}$$

By adding the two quantities in this way it is possible to calculate the overall impedance for the combination of resistor and capacitor.

It is also possible to use Ohm's law to calculate the current and voltage, etc in the normal way.

Capacitive reactance is a key quantity in all forms of electrical electronic circuit. As capacitors are used in virtually all electronic products, understanding how to calculate the reactance and how this interacts with resistors and other electronic components is a key element for many electronic circuit designs. Even though the calculations are relatively straightforward, they are very important in many areas.

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Capacitors in Series & Parallel: details, equations & calculator

There are many instance where it is necessary to calculate the total capacitance of a number of capacitors that are in series or parallel with each other.

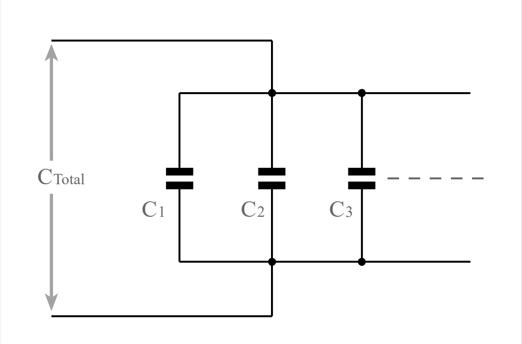
In a variety of areas of electrical and electronic circuit design, installation and use, it can be necessary to place capacitors in series with each other, or in other instances in paralle.

In these instances it is necessary to be able to calculate the total capacitance of the series and parallel capacitor combinations.

There are some easy calculations to use, and also we have included a calculator for calculating the value of two capacitors in series with each other.

Parallel capacitors formula

It is very easy to calculate the total capacitance of a set of capacitors in parallel. The total value is simply the sum of the capacitance values of the individual capacitors.



In theory there is no limit to the number of capacitors that can be added in parallel. Obviously there can be practical limits dependent upon the application, space and other physical limitations.

The overall value of a number of capacitors placed in parallel is simple the sum of the values. This can be expressed on the formula given below:

$$C_{\text{Total}} = C_1 + C_2 + C_3 \ldots\ldots$$

Reasons for using capacitors in parallel

There are several reasons why it may be beneficial to place capacitors in parallel:

- ***To obtain non-preferred capacitance value:*** Like many components, capacitors come in preferred values. For some applications, specific values may be required that may not coincide with the preferred values, or with those that might be available. Almost any value can be made from combining two or more preferred values, although be aware that some capacitors wide tolerance levels so the final value will be subject to these figures.
- ***Increase value of capacitor:*** The most obvious reason for having two or more capacitors in parallel is to increase the value of capacitance available. It may be convenient to use two or more capacitors of a smaller value than a single larger one. Again availability may be an issue and require the use of two capacitors in parallel.
- ***Utilise different capacitors for decoupling different frequencies:*** A single capacitor is not always able to remove all the frequencies that may be present on a voltage supply line etc. To fully achieve this, it is often the practice to use tow capacitors in parallel: one such as an electrolytic with a larger value to remove the low frequency components (the electrolytic capacitor is not good at passing high frequency signals); and one such as a ceramic capacitor with a smaller value for removing the high frequency components (the smaller ceramic capacitor will not have a low enough reactance to pass the low frequency components).

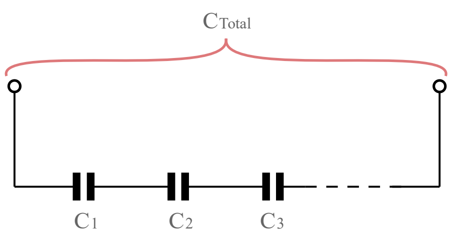
  When using this approach it is necessary to be aware of the effects of spurious series inductance because it is possible for the stray inductance from one capacitor to resonate with the capacitance of the second. These effects do not normally cause a problem, but running two capacitors in parallel can give rise to these combined effects.

- *Distributed decoupling:* On many logic boards where there are many logic ICs it is common practice to distribute the decoupling around the board, typically having a capacitor on each IC, or possibly every other IC, and larger decoupling capacitors placed strategically around the circuit. It is necessary in circumstances like these to be able to calculate the overall capacitance level. Although each capacitor may not be large, the sum of all the capacitors on the board can add up. It is always wise to calculate the total value of all the capacitors in parallel.

Placing capacitors in parallel can provide the advantages detailed above. Using capacitors in parallel provides additional flexibility in their use.

Series capacitors formula

If capacitors are placed in parallel this is a bit akin to increasing the size of the capacitor plates and hence the values of capacitors in parallel can simply be added together. If the capacitors are in series, they cannot simply be added.



Capacitors connected in series

In theory there is no limit to the number of capacitors that can be added in series. Obviously there can be practical limits dependent upon the application, space and other physical limitations.

When capacitors are connected in series, the total capacitance can be determined by taking the reciprocal of the capacitance of each capacitor, and adding these together to give the reciprocal of the total capacitance.

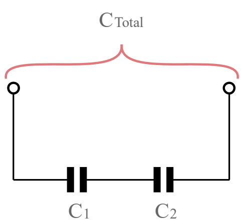
$$\frac{1}{C_{\text{Total}}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \cdot \cdot \cdot \cdot \cdot$$

Two capacitors in series

There are several instances where capacitors may be required to be placed in series. In some circuits, this occurs naturally, for example in some oscillators there may be a capacitor AC voltage divider. In other instances capacitors may be placed in series for a variety of reasons and some examples are given below.

Although the most common combination is to see two capacitors in series, it is possible to place three or more in series.

When calculating the general case for the total capacitance value for a series of capacitors in series, the computation can be a little long winded if done manually. As most networks, only two capacitors are placed in series and it is possible to considerably simplify the formula. This makes manual computation very much easier.



Two capacitors connected in series

$$C_{\text{Total}} = \frac{C_1 \, C_2}{C_1 + C_2}$$

Capacitors in series calculator

The calculator below provides the total capacitance for two capacitors in series. The capacitance can be entered as Farads, μfarads, nanofarads, or picofarads, provided that the same units are used for both capacitors. The answer is provided in the same units as those entered.

Series Capacitor Calculator

Enter Capacitance Values:

C1:		Farads, F;
C2:		Farads, F;

Calculate Clear Data

Results:

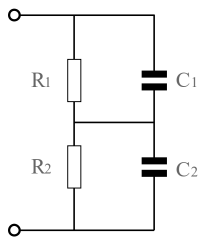
Ctotal:		Farads, F

Precautions for using capacitors in series

Although capacitors do appear in series in a number of circuit configurations like oscillators and the like, capacitors may be used in series to increase the working voltage.

When two capacitors are used in series, then the issue is often that the two capacitors do not share the voltage equally. Differences in leakage current occur between capacitors, especially for capacitors like electrolytic versions and this means that the voltages across the two capacitors can differ greatly, and as a result one may be subject to an over-voltage conditions which could result in the destruction of one or both capacitors. This can occur if the two capacitors have been placed in series to provide an increase in working voltage.

A difference in leakage current can easily result from minor differences in the manufacture, or even differences n the rate at which the two capacitors age – the leakage current in electrolytic capacitors increases with time, especially if they are not used.



Two capacitors connected in series with resistor voltage divider

To assist in sharing the voltage equally across the two capacitors, high value resistors are placed around the capacitors as a potential divider. Values may be of the order 100kΩ or possibly even a little higher, but enough so that the voltages can reliably be divider across both capacitors.

In essence the values of the two resistors should be such that the current flowing through them is at least ten times higher than that of the leakage current. In this way, the voltage will be shared more equally across the capacitors in series. Even when this approach is applied it is good to leave a good margin in the working voltage, especially when electrolytic capacitors are used.

Connecting capacitors in series occurs in many circuits. Knowing how to calculate the overall value, even if it is a rough calculation in your head is very useful. If a more accurate value is needed then the online series capacitor calculator can be very useful.

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Dielectric Constant & Relative Permittivity

The dielectric constant & relative permittivity are key to the operation of capacitors and the determination of the levels of capacitance achievable.

Permittivity and dielectric constant are two terms that are central to capacitor technology. Often talk will be heard of capacitors with different dielectrics being used when selections of electronic components are being made within an electronic circuit design.

Electrolytic capacitors, ceramic capacitors, paper, tantalum capacitors and all the common names for capacitors refer to the dielectric material that is used.

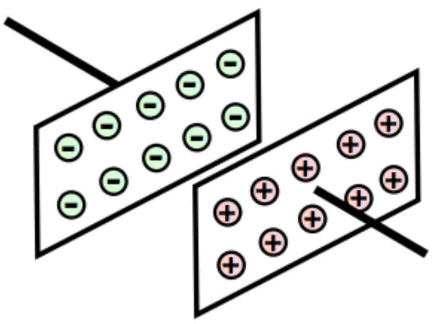
The dielectric material provides the insulation between the capacitor plates, and in addition this it determines many of the characteristics of the capacitor.

The dielectric of the capacitor governs the level of capacitance achievable in a certain volume, the temperature stability whether it is polarised or not. These and many other characteristics are are all a function of the dielectric material used – many properties being governed by the dielectric constant itself.

A selection of capacitors with different dielectrics

Capacitor permittivity and dielectric constant

The terms permittivity and dielectric constant are essentially the same for most purposes, although there are instances where the different terms do have very specific meanings.



The dielectric constant of the material between the two plates governs the levels of capacitance achievable

It is that property of a dielectric material that determines how much electrostatic energy can be stored per unit of volume when unit voltage is applied, and as a result it is of great importance for capacitors and capacitance calculations and the like.

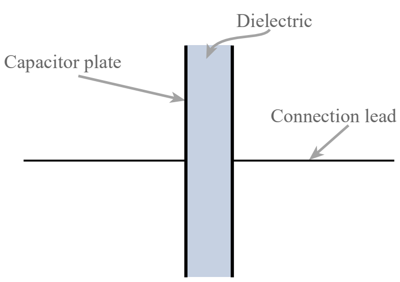
In capacitors, the two plates are kept apart by an insulator - this is the dielectric material that governs many of the properties of the capacitor.

Early capacitors tended to be metal plates that were kept apart by the mechanical construction of the whole assembly.

Vintage capacitor with plates held apart mechanically and with air dielectric

More modern capacitors have an insulating dielectric material placed between the plates. This provides two main advantages:

- ***Separates plates:*** As capacitors become smaller and need to be more robust, it is necessary to place an insulating material between the plates to ensure they remain apart. With capacitors becoming very small and also very close separation between the plates being needed to have the required level of capacitance, it becomes essential to place the insulating dielectric between them.
- ***Increases level of capacitance:*** By selecting the right dielectric, the level of capacitance can be increased considerably when compared to air. and it is possible to achieve very high levels of capacitance in a small volume.



Simplified view of construction of capacitor showing the plates and insulating dielectric

The diagram shows how the way in which a very basic capacitor is constructed with a dielectric between the plates. As most of the electric filed lines pass virtually parallel between the two plates, having the dielectric only between the plates is perfectly permissible.

For real capacitors, they consist of multiple plates between each other to enable the sufficient level of capacitance to be achieved, each with a layer of dielectric insulating material between them.

Other areas where the dielectric constant is important

The dielectric constant and permittivity affect other aspects of electrical and electronic technology. The relative permittivity and dielectric constant are not just important when it comes to capacitors, there are also other areas as well.

- ***RF transmission lines:*** Within coaxial and other forms of feeder the dielectric placed between the inner and outer conductors for coaxial cable, between the two wires for open feeder and between the conductor and ground plane, etc for PCB transmission lines has a major effect on the characteristics in terms of characteristic impedance and velocity factor, etc.
- ***Radio propagation:*** Changes in relative permittivity of the atmosphere can have a major impact on the transmission of radio signals, especially at frequencies above 30 MHz and more. Even slight changes in relative permittivity can cause the radio signal paths to bend, often back towards the earth, causing them to be detected over greater distances.

These examples, and more show that the relative permittivity of a medium can have an impact on many aspects of electronics, radio and other elements of technology and science.

Permittivity & dielectric constant definitions

Definitions of some specific terms related to dielectric constant and permittivity are given below:

- ***Absolute permittivity:*** Absolute permittivity is defined as the measure of permittivity in a vacuum and it is how much resistance is encountered when forming an electric field in a vacuum. The absolute permittivity is normally symbolised by ε_0. The permittivity of free space - a vacuum - is equal to approximately 8.85 x 10^{-12} Farads / metre (F/m)
- ***Relative permittivity:*** Relative permittivity is defined as the permittivity of a given material relative to that of the permittivity of a vacuum. It is normally symbolised by: ε_r.
- ***Static permittivity:*** The static permittivity of a material is defined as its permittivity when exposed to a static electric field. Often a low frequency limit is placed on the material for this measurement. A static

permittivity is often required because the response of a material is a complex relationship related to the frequency of the applied voltage.

- *Dielectric constant:* The dielectric constant is defined as the relative permittivity for a substance or material.

Although these terms may be seen to be related, it is often important to use the correct terms in the required place.

In general permittivity uses the Greek letter epsilon as its symbol: ε.

Relative permittivity (dielectric constant)

Using the fact that the permittivity ε of a medium is governs the charge that can be held by a medium, it can be seen that the formula to determine it is:

$$\varepsilon = \frac{D}{E}$$

Where:
ε = permittivity of the substance in Farads per metre
D = electric flux density
E = electric field strength

It can be seen from the definitions of permittivity that constants are related according to the following equation:

$$\varepsilon_r = \frac{\varepsilon_s}{\varepsilon_0}$$

Where:
ε_r = relative permittivity
ε_s = permittivity of the substance in Farads per metre
ε_0 = permittivity of a vacuum in Farads per metre

Choice of capacitor dielectric

Capacitors use a variety of different substances as their dielectric material. The material is chosen for the properties it provides. One of the major reasons for the choice of a particular dielectric material is its dielectric constant. Those with a high dielectric constant enable high values of capacitance to be achieved - each one having a different permittivity or dielectric constant. This changes the amount of capacitance that the capacitor will have for a given area and spacing.

The dielectric will also need to be chosen to meet requirements such as insulation strength - it must be able to withstand the voltages placed across it with the thickness levels used. It must also be sufficiently stable with variations in temperature, humidity, and voltage, etc.

Popular choices for capacitors are given by the names: aluminium electrolytic capacitors, ceramic capacitors, silver mica capacitors and tantalum capacitors are all commonly used types.

Relative permittivity of common substances

The table below gives the relative permittivity of a number of common substances.

RELATIVE PERMITTIVITY OF COMMON SUBSTANCES

SUBSTANCE	RELATIVE PERMITTIVITY ε_R
Aluminium oxide	8.6
Barium Titanate (Class1)	5 - 450
Barium Titanate (Class 2)	200 - 12000
Calcium titanate	150
Ebonite	2.7 - 2.9
FR4 PCB material	4.8 typically
Glass	5 - 10
Marble	8.3
Mica	5.6 - 8.0
Paper	3.85
Paraffin wax	2 - 2.4
Polyethylene	2.25
Polyimide	2.25
Polypropylene	2.2 - 2.36
Porcelain (ceramic)	4.5 - 6.7
PTFE (Teflon)	2.1
Rubber	2.0 - 2.3
Silicon	11.68
Silicon dioxide	3.9
Strontium titanate	200

RELATIVE PERMITTIVITY OF COMMON SUBSTANCES

SUBSTANCE	RELATIVE PERMITTIVITY ε_R
Air 0°C	1.000594
Air 20°C	1.000528
Carbon monoxide 25°C	1.000634
Carbon dioxide 25°C	1.000904
Hydrogen 0°C	1.000265
Helium 25°C	1.000067
Nitrogen 25°C	1.000538
Sulphur dioxide 22°C	1.00818

The values given above are what may be termed the "static" values of permittivity. They are true for steady state or low frequencies. It is found that the permittivity of a material usually decreases with increasing frequency. It also falls with increasing temperature. These factors are normally taken into account when designing a capacitor for electronics applications.

When the design of a capacitor is undertaken the characteristics of the dielectric form one of the main decisions about the capacitor.

Some materials have a very stable dielectric constant and can be used in high stability capacitors, whereas other dielectric materials enable very high levels of volumetric capacitance to be achieved, i.e. high levels of capacitance in a small volume. Normally there is a balance as no single dielectric has ideal characteristics for everything.

Although ceramic capacitors are very popular there are many different ceramics that can be used. These give rise to ceramic capacitors being denoted by the various names for the ceramic performance levels: C0G, Y5V, X7R, NP0, etc.

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Capacitor ESR, Dissipation Factor, Loss Tangent & Q

Important parameters associated with capacitors include: ESR– equivalent series resistance, dissipation factor, loss tangent, & Q.

Capacitance Tutorial Includes:
Capacitance Capacitor formulas Capacitive reactance Parallel & series capacitors Dielectric constant & relative permittivity Dissipation factor, loss tangent, ESR Capacitor conversion chart

ESR or the equivalent series resistance of the capacitor, its DF or dissipation factor, loss tangent and Q or quality factor are all important factors in the specification of any capacitor.

Factors like the ESR, dissipation factor, loss tangent and Q are important in many aspects of the operation of a capacitor and they can determine the types of application for which the capacitor may be used.

As the four parameters are interlinked, ESR, DF, loss tangent and Q will all be addressed on this page.

ESR, DF and Q are all aspects of the performance of a capacitor that will affect its performance in areas such as RF operation. However ESR, and DF are also particularly important for capacitors operating in power supplies where a high ESR and dissipation factor, DF will result in large amount of power being dissipated in the capacitor.

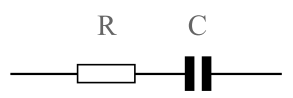
Capacitor ESR, equivalent series resistance

The equivalent series resistance or ESR of a capacitor has an impact on many areas where capacitors may be used.

The equivalent series resistor acts like any other resistor giving rise to voltage drops and dissipating heat. It means that the capacitor is not the perfect capacitor many of us might expect it to be.

The ESR of the capacitor is responsible for the energy dissipated as heat and it is directly proportional to the DF. When analysing a circuit fully, a capacitor should be depicted as its equivalent circuit including the ideal capacitor, but also with its series ESR.

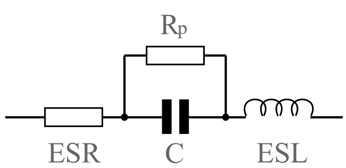
The equivalent series resistance is caused by a number of factors including the Ohmic losses in the leads and plates themselves as well as losses in the dielectric material used between the capacitor plates.



Capacitor ESR, basic equivalent series resistance

Although there can be a focus on the equivalent series resistance or tanδ of a capacitor, it is also worth remembering that the equivalent circuit of a capacitor also includes other equivalent electronic component values as well. It can include an equivalent series inductance as well as a parallel resistance.

In many instances these other components may not be applicable and may complicate the considerations and ESR may be adressed on its own, although it is worth remembering that the other electronic circuit elements also exist.



Equivalent circuit of a capacitor

Capacitors with high values of ESR will dissipate power as heat. For some circuits with only low values of current, this may not be a problem, however in many circuits such as power supply smoothing circuits where current levels are high, the power levels dissipated by the ESR may result in a significant temperature rise.

This needs to be within the operational bounds for the capacitor otherwise damage may result, and this needs to be incorporated within the design of the circuit. If the temperature rise is too high, then the capacitor may be permanently damaged or even destroyed.

For electrolytic capacitors which tend to be the types used in higher current applications, significant temperature rises increases the ageing effects and hence reduce the expected lifetime even if they do not result in actual damage or destruction. This demonstrates the need to be aware of the ESR when selecting the right electronic component for a given electronic circuit design

It is found that when the temperature of a capacitor rises, then generally the ESR increases, although in a non-linear fashion. Increasing frequency also has a similar effect.

Obviously the ESR of a capacitor needs to be as low as possible for all electronic circuit designs so that the operation of the capacitor is as near the ideal as possible. However, in electronic circuits such as smoothing capacitors within power supplies where current levels may be high and source resistances need to be low, the ESR can be a significant factor in the selection of the right electronic component.

Dissipation factor and loss tangent

Although the ESR figure of a capacitor is mentioned more often, dissipation factor and loss tangent are also widely used and closely associated with the capacitor ESR.

Although dissipation factor and loss tangent are effectively the same, they take slightly different views which are useful when designing different types of circuit. Normally the dissipation factor is used at lower frequencies, whereas the loss tangent is more applicable for high frequency applications.

Dissipation factor and loss tangent definitions

In order to better understand both the dissipation factor and the loss tangent it is necessary to provide concise definitions for these terms.

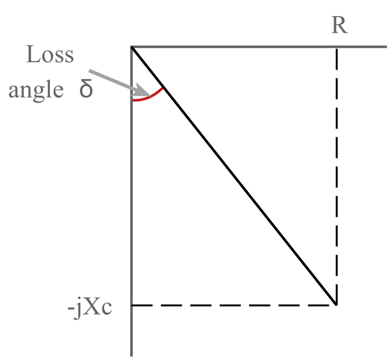
First, let's look at the definition of the dissipation factor:

> ### Dissipation factor definition:
>
> The dissipation factor is defined as the value of the tendency of dielectric materials to absorb some of the energy when an AC signal is applied.

From this it can be seen that the dissipation factor of the capacitor looks more at the way in which the dielectric, especially, of the capacitor absorbs energy.

The loss tangent takes a look at the same issue, but from the viewpoint of the phase angle issues related to the absorption of energy. This figure tends to be used more widely in RF circuit design scenarios.

> ### Loss tangent definition:
>
> The loss tangent is defined as the tangent of the difference of the phase angle between capacitor voltage and capacitor current with respect to the theoretical 90 degree value anticipated, this difference being caused by the dielectric losses within the capacitor. The value δ (Greek letter delta) is also known as the loss angle.



Capacitor loss tangent

From the diagram and definition of the capacitor loss tangent it can be seen that the following equation can be derived.

$$\tan \delta = \text{DF}$$

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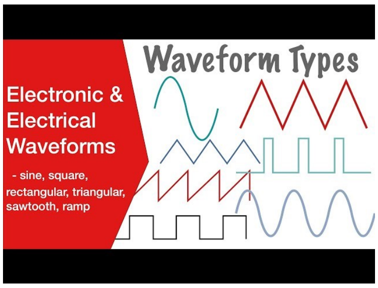

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$$\tan\delta = \frac{1}{Q}$$

$$\tan\delta = \frac{\mathrm{ESR}}{X_c}$$

Where:
δ = loss angle (Greek letter delta)
DF = dissipation factor
Q = quality factor
ESR = equivalent series resistance
X_c = reactance of the capacitor in ohms.

Capacitor Q

It is convenient to define the Q or Quality Factor of a capacitor. It is a fundamental expression of the energy losses in a resonant system. Essentially for a capacitor it is the ratio of the energy stored to that dissipated per cycle.

It can further be deduced that the Q can be expressed as the ratio of the capacitive reactance to the ESR at the frequency of interest:

$$Q = \frac{X_c}{\mathrm{ESR}}$$

Where
Q = the quality factor of te capacitor
X_c = the capacitive reactance of the capacitor in Ohms
ESR = equivalent series resistance in Ohms

As Q can be measured quite easily, and it provides repeatable measurements, it is an ideal method for quantifying the loss in low loss components.

The capacitor Q is an important parameter for circuits like filters and oscillators. In these circuits any losses will result in reduced Q for the capacitor itself and for the whole filter or oscillator resonant circuit. This can result in reduced performance.

Effects of ESR

Equivalent series resistance is generally associated with electrolytic capacitors, and often with tantalum capacitors, because these electronic components generally have higher values of capacitance and the construction of these capacitors leads to relatively high values of series resistance.

Electrolytic capacitors are often used as energy reserves in power supplies, etc to store energy that will be supplied when the rectified voltage waveform falls in value over parts of the cycle, etc.

They can also be used in switching regulators to remove switching spikes, etc.

In both cases, losses due to ESR will reduce the ability of the capacitor to quickly source or sink charge.

For electronic circuits where the capacitor is used at the input, the ESR increases high frequency noise across the capacitor, and this decreases the effectiveness of the capacitor filtering. If the capacitor is used for output smoothing, etc, a higher ESR causes more ripple to be present as the capacitor will be unable to sink and source the required amount of current.

The ESR of a capacitor is particularly important in electronic circuit designs that have a low duty-cycle with high frequency current pulses. In these cases, the ripple voltage resulting from the higher level of ESR will be greater than expected based on capacitance alone.

It may also be found that the ESR will decrease with increasing temperature and this could mean that the ripple decreases as the assembly warms up.

Another issue in some instances is that the resistive element into what may be assumed as a purely reactive circuit can lead to unexpected shifts in phase response, and this might affect the stability of some electronic circuit designs.

ESR specifications

The equivalent series resistance is important in many electronic circuit designs, and accordingly some capacitors are specifically manufactured to provide a low ESR. Even though ESR is important, there does not always seem to be a consistent way of specifying the ESR and this can make it difficult to compare one capacitor with another.

As ESR is dependent upon the operating temperature and the frequency, there are several variables in the specification. It is here that the way in which different manufacturers present their specifications is different.

The most common specification is for the ESR at 25°C and a frequency of 100Hz which is double the line power frequency in Europe, etc, or sometimes it is given at 120Hz as this is double the line power frequency in the USA. Sometimes a formula is presented to enable the ESR to be calculated it other frequencies.

Other capacitor manufacturers may provide the data in other ways, whilst sometimes giving methods to calculate the ESR at the required operating points. In all it can become a little confusing.

It is also interesting to note that for capacitors of comparable size and capacitance-voltage, CV rating, it is found that the electronic component with the higher capacitance and lower voltage rating will have lower ESR . Also the ESR tends to be lower for aluminium electrolytic capacitors with long, thin cases because the resistance of the foil is reduced.

A further point to note is that capacitors with larger overall case sizes can sometimes have a lower ESR as the foil thickness could be greater.

Capacitor ESR, dissipation factor, loss tangent and Q are all important aspects of the loss within a capacitor. They are all linked and essentially different methods of looking at the same issue. However they are used in different areas of circuit design as such capacitor ESR, dissipation factor, loss tangent and Q are all seen in the specification sheets, but for different capacitors used in different areas..

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Capacitor Conversion Chart & Calculator: uF to nF, pF to nF . . .

Capacitor values may be expressed in μF, nF and pF and value conversions often need to be made between them, nF to μF, nF to pF and vice versa.

Capacitance Tutorial Includes:
Capacitance   Capacitor formulas   Capacitive reactance   Parallel & series capacitors   Dielectric constant & relative permittivity   Dissipation factor, loss tangent, ESR   Capacitor conversion chart

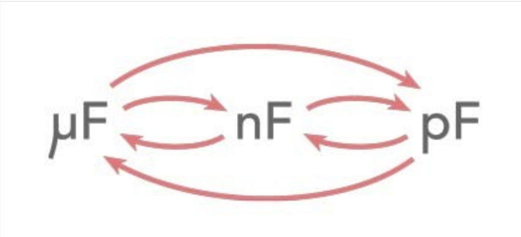
Capacitors are a very common form of electronic component and capacitor values are generally expressed in terms of microfarads, μF (sometimes uF when a micro character is not available), nanofarads, nF and picofarads, pF.

Often there is an overlap between these multipliers. For example 0.1μF can also be expressed as 100nF, and there are many more examples of this type of notation confusion.

Also in some areas the use of nanofarad, nF is less widespread with values being expressed in fractions of a μF and large multiples of picofarads, pF. Under these circumstances it may be necessary to convert to nanofards, nF when components marked in nanofarad are available.

It can sometimes be confusing when a circuit diagram or electronic components list may mention the value in terms of picofarads for example and the listings for an electronic component distributor of electronic components store may mention it in another.

Also when undertaking electronic circuit design, it is necessary to ensure the electronic component values are specified in the current multiple of ten. It could be disastrous to be out by a factor of ten!



The capacitor conversion chart below reveals the equivalents between μF, nF and pF in an easy to use table format. Often when buying from an electronic components distributor or electronic components store, the markings of specifications may use different notations and it may be necessary to convert them.

Capacitor values can be of over 10^9 range, and even more as super capacitors are now being used. To prevent confusion with large numbers of zeros attached to the values of the different capacitors the common prefixes pico (10^{-12}), nano (10^{-9}) and micro (10^{-6}) are widely used. When converting between these it is sometimes useful to have a capacitor conversion chart or capacitor conversion table for the different capacitor values.

A further requirement for capacitance conversion is that for some capacitor marking schemes, the actual capacitance value is given in picofarads, then requiring the value to be converted to the more usual nanofarads or microfarads is required.

Also other forms of electronic component use the same forms of multiplier. Resistors tend not to as their values are measured in Ω and higher multiples like kΩ or &MΩ but inductors are measured in Henries, and values are much smaller. Therefore milli-Henries and micro-Henries are widely used and therefore similar conversions may be required.

Capacitance conversion calculator

The capacitance value conversion calculator below provides easy conversions between values expressed in microfarads: μF, nanofarads: nF and picofarads: pF. Simple enter the value and what it is expressed in, and the value will be displayed in μF, nF and pF, as well as the value in Farads!

Capacitance Conversion Calculator

Convert electrostatic capacitance.

Convert from: pF

Result:

pF

μF

nF

F

Capacitor conversion chart

A chart or table proving an easy translation between micro-farads,μF; nanofarads, nF, and picofarads, pF is given below. This helps reduce the confusion that can occur when having to change between the different multipliers of values.

CAPACITOR VALUE CONVERSION CHART
PF TO NF, M TO NF, ETC . .

MICROFARADS (MF)	NANOFARADS (NF)	PICOFARADS (PF)
0.000001	0.001	1
0.00001	0.01	10
0.0001	0.1	100
0.001	1	1000
0.01	10	10000
0.1	100	100000
1	1000	1000000
10	10000	10000000
100	100000	100000000

This capacitor conversion chart or capacitor conversion table enables quick and easy reference of the different values given for capacitors and conversion between picofarads, nanofarads and microfarads.

Popular capacitor conversions

There are a few popular ways of writing capacitor values. Often for example a ceramic capacitor may be given as a value of 100nF. If used in circuits with electrolytic capacitors, it is often interesting to realise that this is 0.1μF. These useful conversions can help when designing, building, or maintaining circuits.

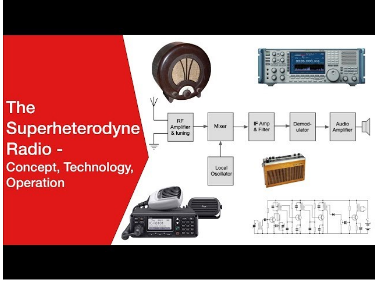
COMMON CAPACITOR CONVERSIONS
100pF = 0.1nF
1000pf = 1 nF
100nF = 0.1μF

When designing circuits or using capacitors in any way, it is often useful to have these capacitor conversions in mind as values transition from picofarads to nanofarads and then nanofarads to microfarads.

A more comprehensive table of conversion factors to convert between the different values, nF to pF, μF to nF etc is given below.

TABLE OF CONVERSION FACTORS TO CONVERT BETWEEN MF, NF, AND PF

CONVERT	MULTIPLY BY:
pF to nF	1×10^{-3}



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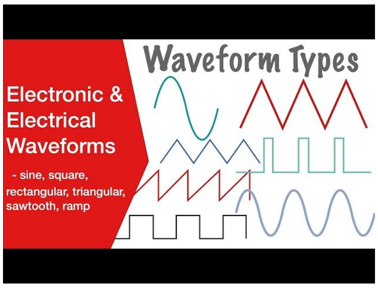

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TABLE OF CONVERSION FACTORS TO CONVERT BETWEEN MF, NF, AND PF

CONVERT	MULTIPLY BY:
pF to μF	1×10^{-6}
nF to pF	1×10^{3}
nF to μF	1×10^{-3}
μF to pF	1×10^{6}
μF to nF	1×10^{3}

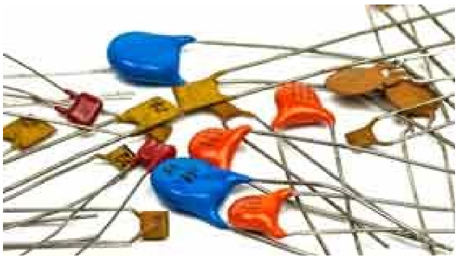
Capacitor conversion nomenclature

Although most modern circuits and component descriptions use the nomenclature of μF, nF and pF for detailing capacitor values, often older circuit diagrams, circuit descriptions and even the components themselves may use a host of non-standard abbreviations and it may not always be clear exactly what they mean.

The main variations for the various capacitance sub-multiples are given below:

- ***Micro-Farad, μF :*** The values for larger value capacitors like electrolytic capacitors, tantalum capacitors, and even some paper capacitors measured in micro-Farads might have been designated in uF, mfd, MFD, MF or UF. All of these refer to the value measured in μF. This terminology is normally associated with electrolytic capacitors and tantalum capacitors.
- ***Nano-Farad, nF:*** The terminology of nF or nano-Farads was not widely used before the standardisation of terminology, and therefore this submultiple did not have a variety of abbreviations. The term nanofarad has come into much greater use in recent years, although in some countries its use is not as widespread, with values being expressed in large numbers of picofarads, e.g. 1000pF for 1 nF, or fractions of a microfarad, e.g. 0.001μF, again for a nanofarad. This terminology is generally associated with ceramic capacitors, metalised film capacitors including surface mount multilayer ceramic capacitors, and even some modern silver mica capacitors.
- ***Pico-Farad, pF:*** Again a variety of abbreviations were used to indicate the value in picoFarads, pF. Terms used included: microromicroFarads, mmfd, MMFD, uff, μμF. All of these refer to values in pF. Capacitor values measured in picofarads are often used in radio frequency, RF circuits and equipment. Accordingly this terminology is used chiefly with ceramic capacitors, but it is also used for silver mica capacitors and some film capacitors.

The standardisation of terminology has assisted in the conversion of values from one submultiple to the next. It has meant that there is considerably less room for misunderstanding. It is easier converting from μF to nF and pF. This is often useful when a circuit diagram may mention a capacitor value mentioned in one way, and the electronic components distributor lists may mention it in another.



The capacitance conversion chart is very useful because different electronic component manufacturers may mark components differently, sometimes labelling as multiple of nanofarad, whereas other manufacturers may mark their equivalent capacitors as a faction of a microfarad and so forth. Obviously the electronic components distributors and electronic component stores will tend to use the manufacturers nomenclature.

Similarly circuit diagrams may mark components differently, often to keep commonality, etc. Accordingly it helps to be able to convert from picofarads to nanofarad and microfarads and vice versa. This can help identify components marked in values expressed in nanofarad when the bill of materials or parts list for the circuit may have values expressed in microfarads, μF and picofarads, pF.

Often it is helpful to be able to use a capacitance conversion calculator like the one above, but often one becomes familiar with the conversions and the popular equivalents like 1000pF is a nanofarad and 100nF is 0.1μF.

When using electronic components and undertaking electronic circuit design, these conversions quickly become second nature, but even so the capacitance conversion tables and calculators can often be very useful. These conversions are obviously useful for capacitors as well as other electronic components like inductors.

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