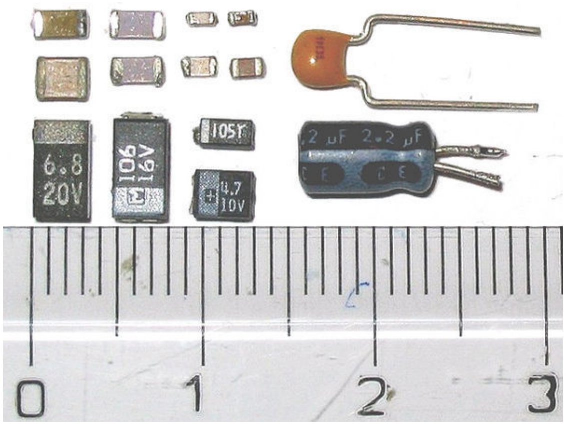
2. Capacitors

Contents

Chapter 1

Capacitor

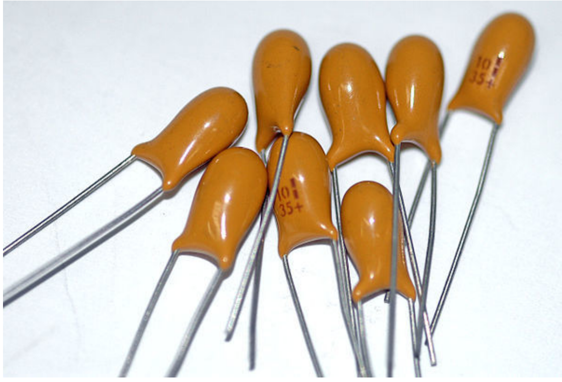
This article is about the electronic component. For the physical phenomenon, see capacitance. For an overview of various kinds of capacitors, see types of capacitor.
“Capacitive” redirects here. For the term used when referring to touchscreens, see capacitive sensing.



Miniature low-voltage capacitors (next to a cm ruler)

A typical electrolytic capacitor

4 electrolytic capacitors of different voltages and capacitance



*Solid electrolyte, resin-dipped 10 μF 35 V tantalum capacitors. The **+** sign indicates the positive lead.*

A **capacitor** (originally known as a **condenser**) is a passive two-terminal electrical component used to store energy electrostatically in an electric field. The forms of practical capacitors vary widely, but all contain at least two electrical conductors (plates) separated by a dielectric (i.e. insulator). The conductors can be thin films, foils or sintered beads of metal or conductive electrolyte, etc. The nonconducting dielectric acts to increase the capacitor’s charge capacity. A dielectric can be glass, ceramic, plastic film, air, vacuum, paper, mica, oxide layer etc. Capacitors are widely used as parts of electrical circuits in many common electrical devices. Unlike a resistor, an ideal capacitor does not dissipate energy. Instead, a capacitor stores energy in the form of an electrostatic field between its plates.

When there is a potential difference across the conductors (e.g., when a capacitor is attached across a battery), an electric field develops across the dielectric, causing positive charge $+Q$ to collect on one plate and negative charge $-Q$ to collect on the other plate. If a battery has been attached to a capacitor for a sufficient amount of time, no current can flow through the capacitor. However, if a time-varying voltage is applied across the leads of the capacitor, a displacement current can flow.

An ideal capacitor is characterized by a single constant value for its capacitance. Capacitance is expressed as the ratio of the electric charge Q on each conductor to the potential difference V between them. The SI unit of capacitance is the farad (F), which is equal to one coulomb per volt (1 C/V). Typical capacitance values range from about 1 pF (10^{-12} F) to about 1 mF (10^{-3} F).

The capacitance is greater when there is a narrower separation between conductors and when the conductors have a larger surface area. In practice, the dielectric between the plates passes a small amount of leakage current and also has an electric field strength limit, known as the breakdown voltage. The conductors and leads introduce an undesired inductance and resistance.

Capacitors are widely used in electronic circuits for blocking direct current while allowing alternating current to pass. In analog filter networks, they smooth the output of power supplies. In resonant circuits they tune radios to particular frequencies. In electric power transmission systems, they stabilize voltage and power flow.[1]

1.1 History

In October 1745, Ewald Georg von Kleist of Pomerania, Germany, found that charge could be stored by connecting a high-voltage electrostatic generator by a wire to a volume of water in a hand-held glass jar.[2] Von Kleist's hand and the water acted as conductors, and the jar as a dielectric (although details of the mechanism were incorrectly identified at the time). Von Kleist found that touching the wire resulted in a powerful spark, much more painful than that obtained from an electrostatic machine. The following year, the Dutch physicist Pieter van Musschenbroek invented a similar capacitor, which was named the Leyden jar, after the University of Leiden where he worked.[3] He also was impressed by the power of the shock he received, writing, “I would not take a second shock for the kingdom of France.”[4]

Daniel Gralath was the first to combine several jars in parallel into a “battery” to increase the charge storage capacity. Benjamin Franklin investigated the Leyden jar and came to the conclusion that the charge was stored on the glass, not in the water as others had assumed. He also adopted the term “battery”,[5][6] (denoting the increasing of power with a row of similar units as in a battery of cannon), subsequently applied to clusters of electrochemical cells.[7] Leyden jars were later made by coating the inside and outside of jars with metal foil, leaving a space at the mouth to prevent arcing between the foils. The earliest unit of capacitance was the jar, equivalent to about 1.11 nanofarads.[8]

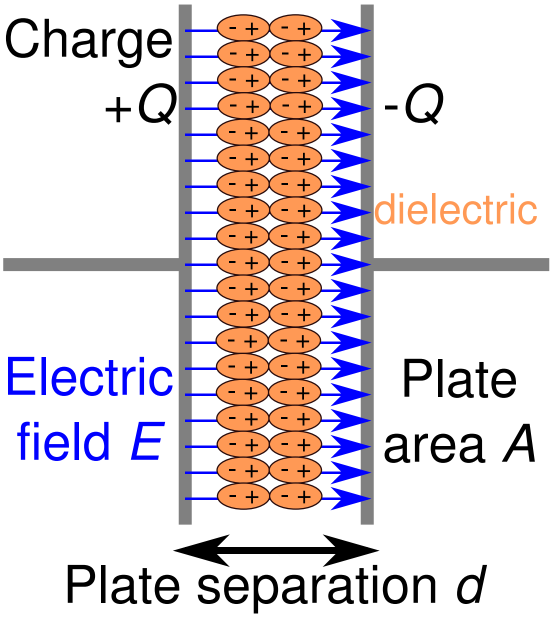
Battery of four Leyden jars in Museum Boerhaave, Leiden, the Netherlands

Leyden jars or more powerful devices employing flat glass plates alternating with foil conductors were used exclusively up until about 1900, when the invention of wireless (radio) created a demand for standard capacitors, and the steady move to higher frequencies required capacitors with lower inductance. More compact construction methods began to be used, such as a flexible dielectric sheet (like oiled paper) sandwiched between sheets of metal foil, rolled or folded into a small package.

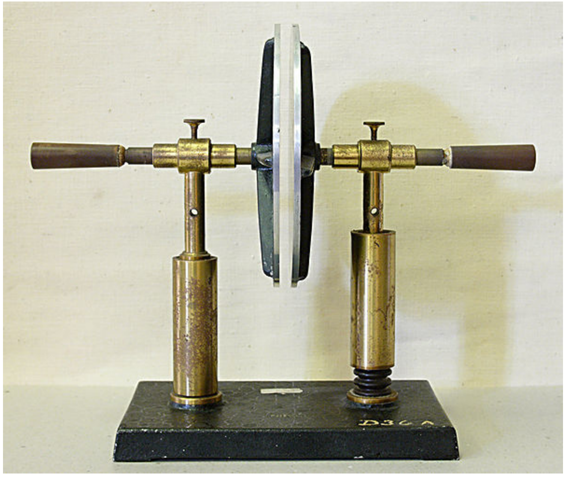
Early capacitors were also known as *condensers*, a term that is still occasionally used today, particularly in high power applications, like automotive systems. The term was first used for this purpose by Alessandro Volta in 1782, with reference to the device's ability to store a higher density of electric charge than a normal isolated conductor.[9]

1.2 Theory of operation

Main article: Capacitance



Charge separation in a parallel-plate capacitor causes an internal electric field. A dielectric (orange) reduces the field and increases the capacitance.



A simple demonstration of a parallel-plate capacitor

1.2.1 Overview

A capacitor consists of two conductors separated by a non-conductive region.[10] The non-conductive region is called the dielectric. In simpler terms, the dielectric is just an electrical insulator. Examples of dielectric media are glass, air, paper, vacuum, and even a semiconductor depletion region chemically identical to the conductors. A capacitor is assumed to be self-contained and isolated, with no net electric charge and no influence from any external electric field. The conductors thus hold equal and opposite charges on their facing surfaces,[11] and the dielectric develops an electric field. In SI units, a capacitance of one farad means that one coulomb of charge on each conductor causes a voltage of one volt across the device.[12]

An ideal capacitor is wholly characterized by a constant capacitance C, defined as the ratio of charge $\pm Q$ on each conductor to the voltage V between them:[10]

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

Because the conductors (or plates) are close together, the opposite charges on the conductors attract one another due to their electric fields, allowing the capacitor to store more charge for a given voltage than if the conductors were separated, giving the capacitor a large capacitance.

Sometimes charge build-up affects the capacitor mechanically, causing its capacitance to vary. In this case, capacitance is defined in terms of incremental changes:

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

1.2.2 Hydraulic analogy

In the hydraulic analogy, a capacitor is analogous to a rubber membrane sealed inside a pipe. This animation illustrates a membrane being repeatedly stretched and un-stretched by the flow of water, which is analogous to a capacitor being repeatedly charged and discharged by the flow of charge.

In the hydraulic analogy, charge carriers flowing through a wire are analogous to water flowing through a pipe. A capacitor is like a rubber membrane sealed inside a pipe. Water molecules cannot pass through the membrane, but some water can move by stretching the membrane. The analogy clarifies a few aspects of capacitors:

- *The current alters the charge on a capacitor*, just as the flow of water changes the position of the membrane. More specifically, the effect of an electric current is to increase the charge of one plate of the capacitor, and decrease the charge of the other plate by an equal amount. This is just as when water flow moves the rubber membrane, it increases the amount of water on one side of the membrane, and decreases the amount of water on the other side.
- *The more a capacitor is charged, the larger its voltage drop*; i.e., the more it “pushes back” against the charging current. This is analogous to the fact that the more a membrane is stretched, the more it pushes back on the water.
- *Charge can flow “through” a capacitor even though no individual electron can get from one side to the*

other. This is analogous to the fact that water can flow through the pipe even though no water molecule can pass through the rubber membrane. Of course, the flow cannot continue in the same direction forever; the capacitor will experience dielectric breakdown, and analogously the membrane will eventually break.

- The *capacitance* describes how much charge can be stored on one plate of a capacitor for a given "push" (voltage drop). A very stretchy, flexible membrane corresponds to a higher capacitance than a stiff membrane.
- A charged-up capacitor is storing potential energy, analogously to a stretched membrane.

1.2.3 Energy of electric field

Work must be done by an external influence to "move" charge between the conductors in a capacitor. When the external influence is removed, the charge separation persists in the electric field and energy is stored to be released when the charge is allowed to return to its equilibrium position. The work done in establishing the electric field, and hence the amount of energy stored, is[13]

$$W = \int_0^Q V \mathrm{d}q = \int_0^Q \frac{q}{C}\mathrm{d}q = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}CV^2 = \frac{1}{2}VQ$$

Here Q is the charge stored in the capacitor, V is the voltage across the capacitor, and C is the capacitance.

In the case of a fluctuating voltage $V(t)$, the stored energy also fluctuates and hence power must flow into or out of the capacitor. This power can be found by taking the time derivative of the stored energy:

$$P = \frac{\mathrm{d}W}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{1}{2}CV^2\right) = CV(t)\frac{\mathrm{d}V}{\mathrm{d}t}$$

1.2.4 Current–voltage relation

The current $I(t)$ through any component in an electric circuit is defined as the rate of flow of a charge $Q(t)$ passing through it, but actual charges—electrons—cannot pass through the dielectric layer of a capacitor. Rather, one electron accumulates on the negative plate for each one that leaves the positive plate, resulting in an electron depletion and consequent positive charge on one electrode that is equal and opposite to the accumulated negative charge on the other. Thus the charge on the electrodes is equal to the integral of the current as well as proportional to the voltage, as discussed above. As with any antiderivative, a constant of integration is added to represent the initial voltage $V(t_0)$. This is the integral form of the capacitor equation:[14]

$$V(t) = \frac{Q(t)}{C} = \frac{1}{C}\int_{t_0}^{t} I(\tau)\mathrm{d}\tau + V(t_0)$$

Taking the derivative of this and multiplying by C yields the derivative form:[15]

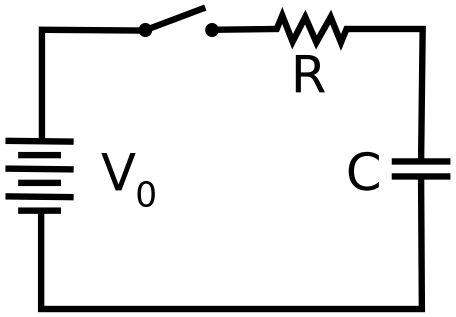
$$I(t) = \frac{\mathrm{d}Q(t)}{\mathrm{d}t} = C\frac{\mathrm{d}V(t)}{\mathrm{d}t}$$

The dual of the capacitor is the inductor, which stores energy in a magnetic field rather than an electric field. Its current-voltage relation is obtained by exchanging current and voltage in the capacitor equations and replacing C with the inductance L.

1.2.5 DC circuits

See also: RC circuit

A series circuit containing only a resistor, a capacitor, a switch and a constant DC source of voltage V_0 is known as a *charging circuit*.[16] If the capacitor is initially uncharged while the switch is open, and the switch is closed at t_0, it follows from Kirchhoff's voltage law that



A simple resistor-capacitor circuit demonstrates charging of a capacitor.

$$V_0 = v_{\text{resistor}}(t) + v_{\text{capacitor}}(t) = i(t)R + \frac{1}{C}\int_{t_0}^{t} i(\tau)\mathrm{d}\tau$$

Taking the derivative and multiplying by C, gives a first-order differential equation:

$$RC\frac{\mathrm{d}i(t)}{\mathrm{d}t} + i(t) = 0$$

At $t = 0$, the voltage across the capacitor is zero and the voltage across the resistor is V_0. The initial current is then $I(0) = V_0/R$. With this assumption, solving the differential equation yields

$$I(t) = \frac{V_0}{R}e^{-\frac{t}{\tau_0}}$$
$$V(t) = V_0\left(1 - e^{-\frac{t}{\tau_0}}\right)$$

where $\tau_0 = RC$ is the *time constant* of the system. As the capacitor reaches equilibrium with the source voltage, the voltages across the resistor and the current through the entire circuit decay exponentially. The case of *discharging* a charged capacitor likewise demonstrates exponential decay, but with the initial capacitor voltage replacing V_0 and the final voltage being zero.

1.2.6 AC circuits

See also: reactance (electronics) and electrical impedance § Deriving the device-specific impedances

Impedance, the vector sum of reactance and resistance, describes the phase difference and the ratio of amplitudes between sinusoidally varying voltage and sinusoidally varying current at a given frequency. Fourier analysis allows any signal to be constructed from a spectrum of frequencies, whence the circuit's reaction to the various frequencies may be found. The reactance and impedance of a capacitor are respectively

$$X = -\frac{1}{\omega C} = -\frac{1}{2\pi f C}$$
$$Z = \frac{1}{j\omega C} = -\frac{j}{\omega C} = -\frac{j}{2\pi f C}$$

where j is the imaginary unit and ω is the angular frequency of the sinusoidal signal. The $-j$ phase indicates that the AC voltage $V = ZI$ lags the AC current by 90°: the positive current phase corresponds to increasing voltage as the capacitor charges; zero current corresponds to instantaneous constant voltage, etc.

Impedance decreases with increasing capacitance and increasing frequency. This implies that a higher-frequency signal or a larger capacitor results in a lower voltage amplitude per current amplitude—an AC "short circuit" or AC coupling. Conversely, for very low frequencies, the reactance will be high, so that a capacitor is nearly an open circuit in AC analysis—those frequencies have been "filtered out".

Capacitors are different from resistors and inductors in that the impedance is *inversely* proportional to the defining characteristic; i.e., capacitance.

A capacitor connected to a sinusoidal voltage source will cause a displacement current to flow through it. In the case that the voltage source is $V_0\cos(\omega t)$, the displacement current can be expressed as:

$$I = C\frac{dV}{dt} = -\omega C V_0 \sin(\omega t)$$

At $\sin(\omega t) = -1$, the capacitor has a maximum (or peak) current whereby $I_0 = \omega C V_0$. The ratio of peak voltage to peak current is due to capacitive reactance (denoted XC).

$$X_C = \frac{V_0}{I_0} = \frac{V_0}{\omega C V_0} = \frac{1}{\omega C}$$

XC approaches zero as ω approaches infinity. If XC approaches 0, the capacitor resembles a short wire that strongly passes current at high frequencies. XC approaches infinity as ω approaches zero. If XC approaches infinity, the capacitor resembles an open circuit that poorly passes low frequencies.

The current of the capacitor may be expressed in the form of cosines to better compare with the voltage of the source:

$$I = -I_0 \sin(\omega t) = I_0 \cos(\omega t + 90^\circ)$$

In this situation, the current is out of phase with the voltage by +π/2 radians or +90 degrees (i.e., the current will lead the voltage by 90°).

1.2.7 Laplace circuit analysis (s-domain)

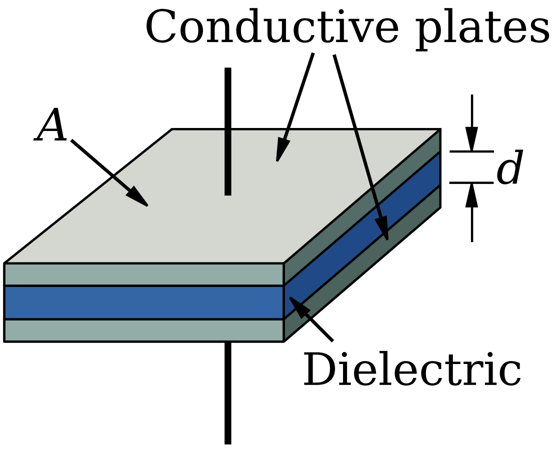
When using the Laplace transform in circuit analysis, the impedance of an ideal capacitor with no initial charge is represented in the *s* domain by:

$$Z(s) = \frac{1}{sC}$$

where

- C is the capacitance, and
- s is the complex frequency.

1.2.8 Parallel-plate model



Dielectric is placed between two conducting plates, each of area A *and with a separation of* d

The simplest capacitor consists of two parallel conductive plates separated by a dielectric (such as air) with permittivity ε . The model may also be used to make qualitative predictions for other device geometries. The plates are considered to extend uniformly over an area A and a charge density $\pm\rho = \pm Q/A$ exists on their surface. Assuming that the width of the plates is much greater than their separation d, the electric field near the centre of the device will be uniform with the magnitude $E = \rho/\varepsilon$. The voltage is defined as the line integral of the electric field between the plates

$$V = \int_0^d E\,\mathrm{d}z = \int_0^d \frac{\rho}{\varepsilon}\,\mathrm{d}z = \frac{\rho d}{\varepsilon} = \frac{Qd}{\varepsilon A}$$

Solving this for $C = Q/V$ reveals that capacitance increases with area of the plates, and decreases as separation between plates increases.

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

The capacitance is therefore greatest in devices made from materials with a high permittivity, large plate area, and small distance between plates.

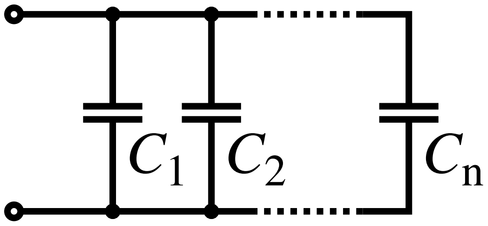
A parallel plate capacitor can only store a finite amount of energy before dielectric breakdown occurs. The capacitor's dielectric material has a dielectric strength U_d which sets the capacitor's breakdown voltage at $V = V_\mathrm{bd} = U_\mathrm{d}d$. The maximum energy that the capacitor can store is therefore

$$E = \frac{1}{2}CV^2 = \frac{1}{2}\frac{\varepsilon A}{d}(U_d d)^2 = \frac{1}{2}\varepsilon A d U_d^2$$

We see that the maximum energy is a function of dielectric volume, permittivity, and dielectric strength per distance. So increasing the plate area while decreasing the separation between the plates while maintaining the same volume has no change on the amount of energy the capacitor can store. Care must be taken when increasing the plate separation so that the above assumption of the distance between plates being much smaller than the area of the plates is still valid for these equations to be accurate. In addition, these equations assume that the electric field is entirely concentrated in the dielectric between the plates. In reality there are fringing fields outside the dielectric, for example between the sides of the capacitor plates, which will increase the effective capacitance of the capacitor. This could be seen as a form of parasitic capacitance. For some simple capacitor geometries this additional capacitance term can be calculated analytically.[17] It becomes negligibly small when the ratio of plate area to separation is large.

1.2.9 Networks

See also: Series and parallel circuits

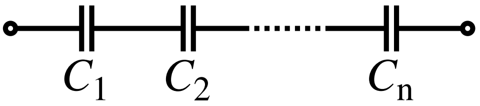


Several capacitors in parallel

For capacitors in parallel Capacitors in a parallel configuration each have the same applied voltage. Their capacitances add up. Charge is apportioned among them by size. Using the schematic diagram to visualize parallel plates, it is apparent that each capacitor contributes to the total surface area.

$$C_\text{eq} = C_1 + C_2 + \cdots + C_n$$

For capacitors in series



Several capacitors in series

Connected in series, the schematic diagram reveals that the separation distance, not the plate area, adds up. The capacitors each store instantaneous charge build-up equal to that of every other capacitor in the series. The total voltage difference from end to end is apportioned to each capacitor according to the inverse of its capacitance. The entire series acts as a capacitor *smaller* than any of its components.

$$\frac{1}{C_\text{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots + \frac{1}{C_n}$$

Capacitors are combined in series to achieve a higher working voltage, for example for smoothing a high voltage power supply. The voltage ratings, which are based on plate separation, add up, if capacitance and leakage currents for each capacitor are identical. In such an application, on occasion, series strings are connected in parallel, forming a matrix. The goal is to maximize the energy storage of the network without overloading any capacitor. For high-energy storage with capacitors in series, some safety considerations must be applied to ensure one capacitor failing and leaking current will not apply too much voltage to the other series capacitors.

Series connection is also sometimes used to adapt polarized electrolytic capacitors for bipolar AC use. See electrolytic capacitor#Designing for reverse bias.

Voltage distribution in parallel-to-series networks. To model the distribution of voltages from a single charged capacitor (A) connected in parallel to a chain of capacitors in series (B_{n}) :

$$(volts)A_{\text{eq}} = A\left(1 - \frac{1}{n+1}\right)$$
$$(volts)B_{1..\text{n}} = \frac{A}{n}\left(1 - \frac{1}{n+1}\right)$$
$$A - B = 0$$

Note: This is only correct if all capacitance values are equal.

The power transferred in this arrangement is:

$$P = \frac{1}{R} \cdot \frac{1}{n+1} A_{\text{volts}} \left(A_{\text{farads}} + B_{\text{farads}}\right)$$

1.3 Non-ideal behavior

Capacitors deviate from the ideal capacitor equation in a number of ways. Some of these, such as leakage current and parasitic effects are linear, or can be assumed to be linear, and can be dealt with by adding virtual components to the equivalent circuit of the capacitor. The usual methods of network analysis can then be applied. In other cases, such as with breakdown voltage, the effect is nonlinear and normal (i.e., linear) network analysis cannot be used, the effect must be dealt with separately. There is yet another group, which may be linear but invalidate the assumption in the analysis that capacitance is a constant. Such an example is temperature dependence. Finally, combined parasitic effects such as inherent inductance, resistance, or dielectric losses can exhibit non-uniform behavior at variable frequencies of operation.

1.3.1 Breakdown voltage

Main article: Breakdown voltage

Above a particular electric field, known as the dielectric strength *Eds*, the dielectric in a capacitor becomes conductive. The voltage at which this occurs is called the breakdown voltage of the device, and is given by the product of the dielectric strength and the separation between the conductors,[18]

$$V_{\text{bd}} = E_{\text{ds}} d$$

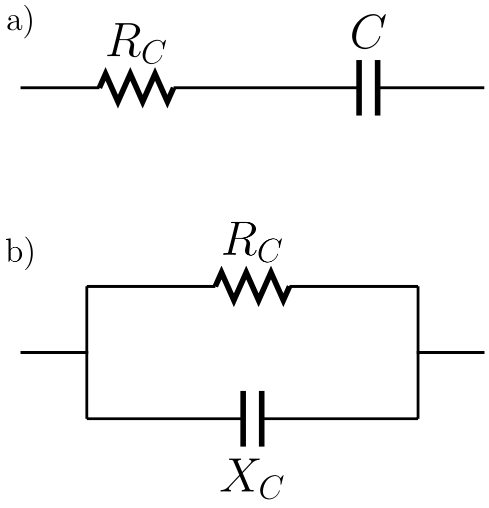
The maximum energy that can be stored safely in a capacitor is limited by the breakdown voltage. Due to the scaling of capacitance and breakdown voltage with dielectric thickness, all capacitors made with a particular dielectric have approximately equal maximum energy density, to the extent that the dielectric dominates their volume.[19]

For air dielectric capacitors the breakdown field strength is of the order 2 to 5 MV/m; for mica the breakdown is 100 to 300 MV/m; for oil, 15 to 25 MV/m; it can be much less when other materials are used for the dielectric.[20] The dielectric is used in very thin layers and so absolute breakdown voltage of capacitors is limited. Typical ratings for capacitors used for general electronics applications range from a few volts to 1 kV. As the voltage increases, the dielectric must be thicker, making high-voltage capacitors larger per capacitance than those rated for lower voltages. The breakdown voltage is critically affected by factors such as the geometry of the capacitor conductive parts; sharp edges or points increase the electric field strength at that point and can lead to a local breakdown. Once this starts to happen, the breakdown quickly tracks through the dielectric until it reaches the opposite plate, leaving carbon behind and causing a short (or relatively low resistance) circuit. The results can be explosive as the short in the capacitor draws current from the surrounding circuitry and dissipates the energy.[21]

The usual breakdown route is that the field strength becomes large enough to pull electrons in the dielectric from their atoms thus causing conduction. Other scenarios are possible, such as impurities in the dielectric, and, if the dielectric is of a crystalline nature, imperfections in the crystal structure can result in an avalanche breakdown as seen in semi-conductor devices. Breakdown voltage is also affected by pressure, humidity and temperature.[22]

1.3.2 Equivalent circuit

An ideal capacitor only stores and releases electrical energy, without dissipating any. In reality, all capacitors have imperfections within the capacitor's material that create resistance. This is specified as the *equivalent series resistance* or **ESR** of a component. This adds a real component to the impedance:



Two different circuit models of a real capacitor

$$R_{\text{C}} = Z + R_{\text{ESR}} = \frac{1}{j\omega C} + R_{\text{ESR}}$$

As frequency approaches infinity, the capacitive impedance (or reactance) approaches zero and the ESR becomes significant. As the reactance becomes negligible, power dissipation approaches PRMS = VRMS^2 /RESR.

Similarly to ESR, the capacitor's leads add *equivalent series inductance* or **ESL** to the component. This is usually significant only at relatively high frequencies. As inductive reactance is positive and increases with frequency, above a certain frequency capacitance will be canceled by inductance. High-frequency engineering involves accounting for the inductance of all connections and components.

If the conductors are separated by a material with a small conductivity rather than a perfect dielectric, then a small leakage current flows directly between them. The capacitor therefore has a finite parallel resistance,[12] and slowly discharges over time (time may vary greatly depending on the capacitor material and quality).

1.3.3 Q factor

The quality factor (or *Q*) of a capacitor is the ratio of its reactance to its resistance at a given frequency, and is a measure of its efficiency. The higher the Q factor of the capacitor, the closer it approaches the behavior of an ideal, lossless, capacitor.

The Q factor of a capacitor can be found through the following formula:

$$Q = \frac{X_C}{R_C} = \frac{1}{\omega C R_C},$$

where ω is angular frequency, C is the capacitance, X_C is the capacitive reactance, and R_C is the series resistance of the capacitor.

1.3.4 Ripple current

Ripple current is the AC component of an applied source (often a switched-mode power supply) whose frequency may be constant or varying. Ripple current causes heat to be generated within the capacitor due to the dielectric losses caused by the changing field strength together with the current flow across the slightly resistive supply lines or the electrolyte in the capacitor. The equivalent series resistance (ESR) is the amount of internal series resistance one would add to a perfect capacitor to model this. Some types of capacitors, primarily tantalum and aluminum electrolytic capacitors, as well as some film capacitors have a specified rating value for maximum ripple current.

- Tantalum electrolytic capacitors with solid manganese dioxide electrolyte are limited by ripple current and generally have the highest ESR ratings in the capacitor family. Exceeding their ripple limits can lead to shorts and burning parts.
- Aluminum electrolytic capacitors, the most common type of electrolytic, suffer a shortening of life expectancy at higher ripple currents. If ripple current exceeds the rated value of the capacitor, it tends to result in explosive failure.
- Ceramic capacitors generally have no ripple current limitation and have some of the lowest ESR ratings.
- Film capacitors have very low ESR ratings but exceeding rated ripple current may cause degradation failures.

1.3.5 Capacitance instability

The capacitance of certain capacitors decreases as the component ages. In ceramic capacitors, this is caused by degradation of the dielectric. The type of dielectric, ambient operating and storage temperatures are the most significant aging factors, while the operating voltage has a smaller effect. The aging process may be reversed by heating the component above the Curie point. Aging is fastest near the beginning of life of the component, and the device stabilizes over time.[23] Electrolytic capacitors age as the electrolyte evaporates. In contrast with ceramic capacitors, this occurs towards the end of life of the component.

Temperature dependence of capacitance is usually expressed in parts per million (ppm) per °C. It can usually be taken as a broadly linear function but can be noticeably non-linear at the temperature extremes. The temperature coefficient can be either positive or negative, sometimes even amongst different samples of the same type. In other words, the spread in the range of temperature coefficients can encompass zero. See the data sheet in the leakage current section above for an example.

Capacitors, especially ceramic capacitors, and older designs such as paper capacitors, can absorb sound waves resulting in a microphonic effect. Vibration moves the plates, causing the capacitance to vary, in turn inducing AC current. Some dielectrics also generate piezoelectricity. The resulting interference is especially problematic in audio applications, potentially causing feedback or unintended recording. In the reverse microphonic effect, the varying electric field between the capacitor plates exerts a physical force, moving them as a speaker. This can generate audible sound, but drains energy and stresses the dielectric and the electrolyte, if any.

1.3.6 Current and voltage reversal

Current reversal occurs when the current changes direction. Voltage reversal is the change of polarity in a circuit. Reversal is generally described as the percentage of the maximum rated voltage that reverses polarity. In DC circuits, this will usually be less than 100% (often in the range of 0 to 90%), whereas AC circuits experience 100% reversal.

In DC circuits and pulsed circuits, current and voltage reversal are affected by the damping of the system. Voltage reversal is encountered in RLC circuits that are under-damped. The current and voltage reverse direction, forming a harmonic oscillator between the inductance and capacitance. The current and voltage will tend to oscillate and may reverse direction several times, with each peak being lower than the previous, until the system reaches an equilibrium. This is often referred to as ringing. In comparison, critically damped or over-damped systems usually do not experience a voltage reversal. Reversal is also encountered in AC circuits, where the peak current will be equal in each direction.

For maximum life, capacitors usually need to be able to handle the maximum amount of reversal that a system will experience. An AC circuit will experience 100% voltage reversal, while under-damped DC circuits will experience less than 100%. Reversal creates excess electric fields in the dielectric, causes excess heating of both the dielectric and the conductors, and can dramatically shorten the life expectancy of the capacitor. Reversal ratings will often affect the design considerations for the capacitor, from the choice of dielectric materials and voltage ratings to the types of internal connections used.[24]

1.3.7 Dielectric absorption

Capacitors made with some types of dielectric material show "dielectric absorption" or “soakage”. On discharging a capacitor and disconnecting it, after a short time it may develop a voltage due to hysteresis in the dielectric. This effect can be objectionable in applications such as precision sample and hold circuits.

1.3.8 Leakage

Leakage is equivalent to a resistor in parallel with the capacitor. Constant exposure to heat can cause dielectric breakdown and excessive leakage, a problem often seen in older vacuum tube circuits, particularly where oiled paper and foil capacitors were used. In many vacuum tube circuits, interstage coupling capacitors are used to conduct a varying signal from the plate of one tube to the grid circuit of the next stage. A leaky capacitor can cause the grid circuit voltage to be raised from its normal bias setting, causing excessive current or signal distortion in the downstream tube. In power amplifiers this can cause the plates to glow red, or current limiting resistors to overheat, even fail. Similar considerations apply to component fabricated solid-state (transistor) amplifiers, but owing to lower heat production and the use of modern polyester dielectric barriers this once-common problem has become relatively rare.

1.3.9 Electrolytic failure from disuse

Aluminum electrolytic capacitors are *conditioned* when manufactured by applying a voltage sufficient to initiate the proper internal chemical state. This state is maintained by regular use of the equipment. In former times, roughly 30 years ago, if a system using electrolytic capacitors is unused for a long period of time it can lose its conditioning. Sometimes they fail with a short circuit when next operated. For further informations see Aluminum electrolytic capacitor#Capacitor behavior after storage or disuse

1.4 Capacitor types

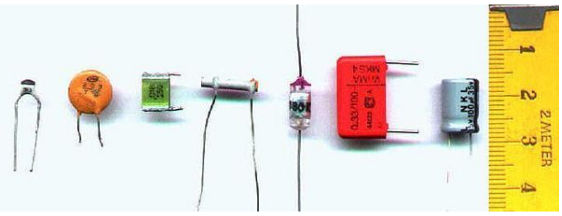
Main article: Types of capacitor

Practical capacitors are available commercially in many different forms. The type of internal dielectric, the structure of the plates and the device packaging all strongly affect the characteristics of the capacitor, and its applications.

Values available range from very low (picofarad range; while arbitrarily low values are in principle possible, stray (parasitic) capacitance in any circuit is the limiting factor) to about 5 kF supercapacitors.

Above approximately 1 microfarad electrolytic capacitors are usually used because of their small size and low cost compared with other types, unless their relatively poor stability, life and polarised nature make them unsuitable. Very high capacity supercapacitors use a porous carbon-based electrode material.

1.4.1 Dielectric materials



Capacitor materials. From left: multilayer ceramic, ceramic disc, multilayer polyester film, tubular ceramic, polystyrene, metalized polyester film, aluminum electrolytic. Major scale divisions are in centimetres.

Most types of capacitor include a dielectric spacer, which increases their capacitance. These dielectrics are most often insulators. However, low capacitance devices are available with a vacuum between their plates, which allows extremely high voltage operation and low losses. Variable capacitors with their plates open to the atmosphere were commonly used in radio tuning circuits. Later designs use polymer foil dielectric between the moving and stationary plates, with no significant air space between them.

In order to maximise the charge that a capacitor can hold, the dielectric material needs to have as high a permittivity as possible, while also having as high a breakdown voltage as possible.

Several solid dielectrics are available, including paper, plastic, glass, mica and ceramic materials. Paper was used extensively in older devices and offers relatively high voltage performance. However, it is susceptible to water absorption, and has been largely replaced by plastic film capacitors. Plastics offer better stability and ageing performance, which makes them useful in timer circuits, although they may be limited to low operating temperatures and frequencies. Ceramic capacitors are generally small, cheap and useful for high frequency applications, although their capacitance varies strongly with voltage and they age poorly. They are broadly categorized as class 1 dielectrics, which have predictable variation of capacitance with temperature or class 2 dielectrics, which can operate at higher voltage. Glass and mica capacitors are extremely reliable, stable and tolerant to high temperatures and voltages, but are too expensive for most mainstream applications. Electrolytic capacitors and supercapacitors are used to store small and larger amounts of energy, respectively, ceramic capacitors are often used in resonators, and parasitic capacitance occurs in circuits wherever the simple conductor-insulator-conductor structure is formed unintentionally by the configuration of the circuit layout.

Electrolytic capacitors use an aluminum or tantalum plate with an oxide dielectric layer. The second electrode is a liquid electrolyte, connected to the circuit by another foil plate. Electrolytic capacitors offer very high capacitance but suffer from poor tolerances, high instability, gradual loss of capacitance especially when subjected to heat, and high leakage current. Poor quality capacitors may leak electrolyte, which is harmful to printed circuit boards. The conductivity of the electrolyte drops at low temperatures, which increases equivalent series resistance. While widely used for power-supply conditioning, poor high-frequency characteristics make them unsuitable for many applications. Electrolytic capacitors will self-degrade if unused for a period (around a year), and when full power is applied may short circuit, permanently damaging the capacitor and usually blowing a fuse or causing failure of rectifier diodes (for instance, in older equipment, arcing in rectifier tubes). They can be restored before use (and damage) by gradually applying the operating voltage, often done on antique vacuum tube equipment over a period of 30 minutes by using a variable transformer to supply AC power. Unfortunately, the use of this technique may be less satisfactory for some solid state equipment, which may be damaged by operation below its normal power range, requiring that the power supply first be isolated from the consuming circuits. Such remedies may not be applicable to modern high-frequency power supplies as these produce full output voltage even with reduced input.

Tantalum capacitors offer better frequency and temperature characteristics than aluminum, but higher dielectric absorption and leakage.[25]

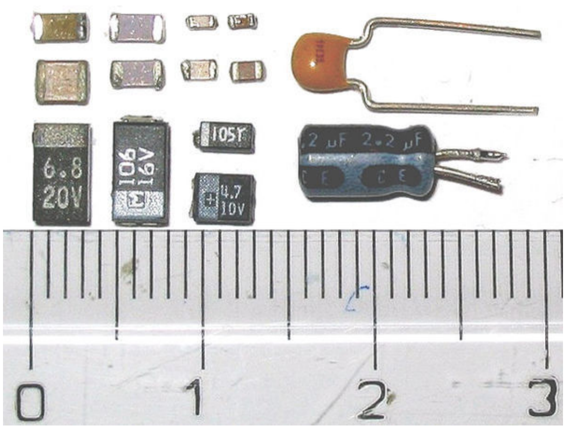
Polymer capacitors (OS-CON, OC-CON, KO, AO) use solid conductive polymer (or polymerized organic semiconductor) as electrolyte and offer longer life and lower ESR at higher cost than standard electrolytic capacitors.

A feedthrough capacitor is a component that, while not serving as its main use, has capacitance and is used to conduct signals through a conductive sheet.

Several other types of capacitor are available for specialist applications. Supercapacitors store large amounts of energy. Supercapacitors made from carbon aerogel, carbon nanotubes, or highly porous electrode materials, offer extremely high capacitance (up to 5 kF as of 2010) and can be used in some applications instead of rechargeable batteries. Alternating current capacitors are specifically designed to work on line (mains) voltage AC power circuits. They are commonly used in electric motor circuits and are often designed to handle large currents, so they tend to be physically large. They are usually ruggedly packaged, often in metal cases that can be easily grounded/earthed.

They also are designed with direct current breakdown voltages of at least five times the maximum AC voltage.

1.4.2 Structure

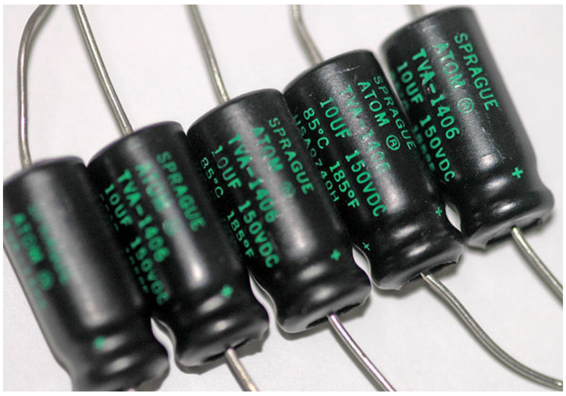


Capacitor packages: SMD ceramic at top left; SMD tantalum at bottom left; through-hole tantalum at top right; through-hole electrolytic at bottom right. Major scale divisions are cm.

The arrangement of plates and dielectric has many variations depending on the desired ratings of the capacitor. For small values of capacitance (microfarads and less), ceramic disks use metallic coatings, with wire leads bonded to the coating. Larger values can be made by multiple stacks of plates and disks. Larger value capacitors usually use a metal foil or metal film layer deposited on the surface of a dielectric film to make the plates, and a dielectric film of impregnated paper or plastic – these are rolled up to save space. To reduce the series resistance and inductance for long plates, the plates and dielectric are staggered so that connection is made at the common edge of the rolled-up plates, not at the ends of the foil or metalized film strips that comprise the plates.

The assembly is encased to prevent moisture entering the dielectric – early radio equipment used a cardboard tube sealed with wax. Modern paper or film dielectric capacitors are dipped in a hard thermoplastic. Large capacitors for high-voltage use may have the roll form compressed to fit into a rectangular metal case, with bolted terminals and bushings for connections. The dielectric in larger capacitors is often impregnated with a liquid to improve its properties.

Capacitors may have their connecting leads arranged in many configurations, for example axially or radially. “Axial” means that the leads are on a common axis, typically the axis of the capacitor’s cylindrical body – the leads extend from opposite ends. Radial leads might more accurately be referred to as tandem; they are rarely actually aligned along radii of the body’s circle, so the term is inexact, although universal. The leads (until bent) are usually in planes parallel to that of the flat body of the capacitor, and extend in the same direction; they are often parallel as manufactured.



Several axial-lead electrolytic capacitors

Small, cheap discoidal ceramic capacitors have existed since the 1930s, and remain in widespread use. Since the 1980s, surface mount packages for capacitors have been widely used. These packages are extremely small and lack connecting leads, allowing them to be soldered directly onto the surface of printed circuit boards. Surface mount components avoid undesirable high-frequency effects due to the leads and simplify automated assembly, although manual handling is made difficult due to their small size.

Mechanically controlled variable capacitors allow the plate spacing to be adjusted, for example by rotating or sliding a set of movable plates into alignment with a set of stationary plates. Low cost variable capacitors squeeze together alternating layers of aluminum and plastic with a screw. Electrical control of capacitance is achievable with varactors (or varicaps), which are reverse-biased semiconductor diodes whose depletion region width varies with applied voltage. They are used in phase-locked loops, amongst other applications.

1.5 Capacitor markings

Most capacitors have numbers printed on their bodies to indicate their electrical characteristics. Larger capacitors like electrolytics usually display the actual capacitance together with the unit (for example, **220 µF**). Smaller capacitors like ceramics, however, use a shorthand consisting of three numeric digits and a letter, where the digits indicate the capacitance in pF (calculated as XY × 10^Z for digits XYZ) and the letter indicates the tolerance (J, K or M for ±5%, ±10% and ±20% respectively).

Additionally, the capacitor may show its working voltage, temperature and other relevant characteristics.

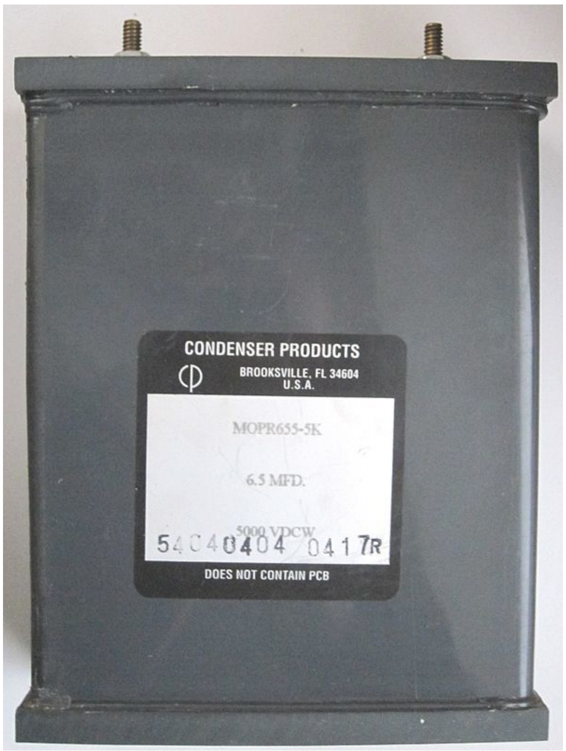
For typographical reasons, some manufacturers print “MF” on capacitors to indicate microfarads (µF).[26]

1.5.1 Example

A capacitor with the text **473K 330V** on its body has a capacitance of 47×10^3 pF = 47 nF (±10%) with a working voltage of 330 V. The working voltage of a capacitor is the highest voltage that can be applied across it without undue risk of breaking down the dielectric layer.

1.6 Applications

Main article: Applications of capacitors



This mylar-film, oil-filled capacitor has very low inductance and low resistance, to provide the high-power (70 megawatt) and high speed (1.2 microsecond) discharge needed to operate a dye laser.

1.6.1 Energy storage

A capacitor can store electric energy when disconnected from its charging circuit, so it can be used like a temporary battery, or like other types of rechargeable energy storage system.[27] Capacitors are commonly used in electronic devices to maintain power supply while batteries are being changed. (This prevents loss of information in volatile memory.)

Conventional capacitors provide less than 360 joules per kilogram of energy density, whereas a conventional alkaline battery has a density of 590 kJ/kg.

In car audio systems, large capacitors store energy for the amplifier to use on demand. Also for a flash tube a capacitor is used to hold the high voltage.

1.6.2 Pulsed power and weapons

Groups of large, specially constructed, low-inductance high-voltage capacitors (*capacitor banks*) are used to supply huge pulses of current for many pulsed power applications. These include electromagnetic forming, Marx generators, pulsed lasers (especially TEA lasers), pulse forming networks, radar, fusion research, and particle accelerators.

Large capacitor banks (reservoir) are used as energy sources for the exploding-bridgewire detonators or slapper detonators in nuclear weapons and other specialty weapons. Experimental work is under way using banks of capacitors as power sources for electromagnetic armour and electromagnetic railguns and coilguns.

1.6.3 Power conditioning

A 10,000 microfarad capacitor in an amplifier power supply

Reservoir capacitors are used in power supplies where they smooth the output of a full or half wave rectifier. They can also be used in charge pump circuits as the energy storage element in the generation of higher voltages than the input voltage.

Capacitors are connected in parallel with the power circuits of most electronic devices and larger systems (such as factories) to shunt away and conceal current fluctuations from the primary power source to provide a “clean” power supply for signal or control circuits. Audio equipment, for example, uses several capacitors in this way, to shunt away power line hum before it gets into the signal circuitry. The capacitors act as a local reserve for the DC power source, and bypass AC currents from the power supply. This is used in car audio applications, when a stiffening capacitor compensates for the inductance and resistance of the leads to the lead-acid car battery.

Power factor correction

A high-voltage capacitor bank used for power factor correction on a power transmission system

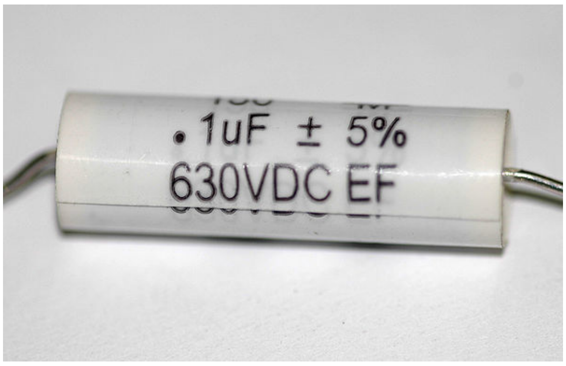
In electric power distribution, capacitors are used for power factor correction. Such capacitors often come as three capacitors connected as a three phase load. Usually, the values of these capacitors are given not in farads but rather as a reactive power in volt-amperes reactive (var). The purpose is to counteract inductive loading from devices like electric motors and transmission lines to make the load appear to be mostly resistive. Individual motor or lamp loads may have capacitors for power factor correction, or larger sets of capacitors (usually with automatic switching devices) may be installed at a load center within a building or in a large utility substation.

1.6.4 Suppression and coupling

Signal coupling

Main article: capacitive coupling

Because capacitors pass AC but block DC signals (when charged up to the applied dc voltage), they are often used to separate the AC and DC components of a signal. This method is known as *AC coupling* or “capacitive coupling”. Here, a large value of capacitance, whose value need not be accurately controlled, but whose reactance is small at the signal frequency, is employed.



Polyester film capacitors are frequently used as coupling capacitors.

Decoupling

Main article: decoupling capacitor

A decoupling capacitor is a capacitor used to protect one part of a circuit from the effect of another, for instance to suppress noise or transients. Noise caused by other circuit elements is shunted through the capacitor, reducing the effect they have on the rest of the circuit. It is most commonly used between the power supply and ground. An alternative name is *bypass capacitor* as it is used to bypass the power supply or other high impedance component of a circuit.

Decoupling capacitors need not always be discrete components. Capacitors used in these applications may be built in to a printed circuit board, between the various layers. These are often referred to as embedded capacitors.[28] The layers in the board contributing to the capacitive properties also function as power and ground planes, and have a dielectric in between them, enabling them to operate as a parallel plate capacitor.

High-pass and low-pass filters

Further information: High-pass filter and Low-pass filter

Noise suppression, spikes, and snubbers

Further information: High-pass filter and Low-pass filter

When an inductive circuit is opened, the current through the inductance collapses quickly, creating a large voltage across the open circuit of the switch or relay. If the inductance is large enough, the energy will generate a spark, causing the contact points to oxidize, deteriorate, or sometimes weld together, or destroying a solid-state switch. A snubber capacitor across the newly opened circuit creates a path for this impulse to bypass the contact points, thereby preserving their life; these were commonly found in contact breaker ignition systems, for instance. Similarly, in smaller scale circuits, the spark may not be enough to damage the switch but will still radiate undesirable radio frequency interference (RFI), which a filter capacitor absorbs. Snubber capacitors are usually employed with a low-value resistor in series, to dissipate energy and minimize RFI. Such resistor-capacitor combinations are available in a single package.

Capacitors are also used in parallel to interrupt units of a high-voltage circuit breaker in order to equally distribute the voltage between these units. In this case they are called grading capacitors.

In schematic diagrams, a capacitor used primarily for DC charge storage is often drawn vertically in circuit diagrams with the lower, more negative, plate drawn as an arc. The straight plate indicates the positive terminal of the device, if it is polarized (see electrolytic capacitor).

1.6.5 Motor starters

Main article: motor capacitor

In single phase squirrel cage motors, the primary winding within the motor housing is not capable of starting a rotational motion on the rotor, but is capable of sustaining one. To start the motor, a secondary "start" winding has a series non-polarized *starting capacitor* to introduce a lead in the sinusoidal current. When the secondary (start) winding is placed at an angle with respect to the primary (run) winding, a rotating electric field is created. The force of the rotational field is not constant, but is sufficient to start the rotor spinning. When the rotor comes close to operating speed, a centrifugal switch (or current-sensitive relay in series with the main winding) disconnects the capacitor. The start capacitor is typically mounted to the side of the motor housing. These are called capacitor-start motors, that have relatively high starting torque. Typically they can have up-to four times as much starting torque than a split-phase motor and are used on applications such as compressors, pressure washers and any small device requiring high starting torques.

Capacitor-run induction motors have a permanently connected phase-shifting capacitor in series with a second winding. The motor is much like a two-phase induction motor.

Motor-starting capacitors are typically non-polarized electrolytic types, while running capacitors are conventional paper or plastic film dielectric types.

1.6.6 Signal processing

The energy stored in a capacitor can be used to represent information, either in binary form, as in DRAMs, or in analogue form, as in analog sampled filters and CCDs. Capacitors can be used in analog circuits as components of integrators or more complex filters and in negative feedback loop stabilization. Signal processing circuits also use capacitors to integrate a current signal.

Tuned circuits

Capacitors and inductors are applied together in tuned circuits to select information in particular frequency bands. For example, radio receivers rely on variable capacitors to tune the station frequency. Speakers use passive analog crossovers, and analog equalizers use capacitors to select different audio bands.

The resonant frequency f of a tuned circuit is a function of the inductance (L) and capacitance (C) in series, and is given by:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

where L is in henries and C is in farads.

1.6.7 Sensing

Main article: capacitive sensing

Main article: Capacitive displacement sensor

Most capacitors are designed to maintain a fixed physical structure. However, various factors can change the structure of the capacitor, and the resulting change in capacitance can be used to sense those factors.

Changing the dielectric:

> The effects of varying the characteristics of the **dielectric** can be used for sensing purposes. Capacitors with an exposed and porous dielectric can be used to measure humidity in air. Capacitors are used to accurately measure the fuel level in airplanes; as the fuel covers more of a pair of plates, the circuit capacitance increases.

Changing the distance between the plates:

> Capacitors with a flexible plate can be used to measure strain or pressure. Industrial pressure transmitters used for process control use pressure-sensing diaphragms, which form a capacitor plate of an oscillator circuit. Capacitors are used as the sensor in condenser microphones, where one plate is moved by air pressure, relative to the fixed position of the other

> plate. Some accelerometers use MEMS capacitors etched on a chip to measure the magnitude and direction of the acceleration vector. They are used to detect changes in acceleration, in tilt sensors, or to detect free fall, as sensors triggering airbag deployment, and in many other applications. Some fingerprint sensors use capacitors. Additionally, a user can adjust the pitch of a theremin musical instrument by moving their hand since this changes the effective capacitance between the user's hand and the antenna.

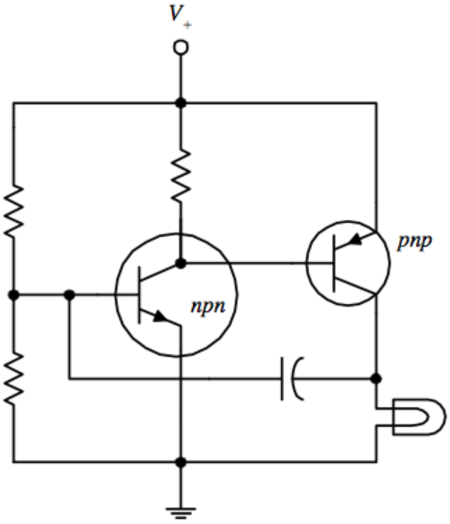
Changing the effective area of the plates:

> Capacitive touch switches are now used on many consumer electronic products.

1.6.8 Oscillators

Further information: Hartley oscillator

A capacitor can possess spring-like qualities in an oscillator circuit. In the image example, a capacitor acts to influence the biasing voltage at the npn transistor's base. The resistance values of the voltage-divider resistors and the capacitance value of the capacitor together control the oscillatory frequency.



Example of a simple oscillator that requires a capacitor to function

1.7 Hazards and safety

Capacitors may retain a charge long after power is removed from a circuit; this charge can cause dangerous or even potentially fatal shocks or damage connected equipment. For example, even a seemingly innocuous device such as a disposable camera flash unit powered by a 1.5 volt AA battery contains a capacitor which may be charged to over 300 volts. This is easily capable of delivering a shock. Service procedures for electronic devices usually include instructions to discharge large or high-voltage capacitors, for instance using a Brinkley stick. Capacitors may also have built-in discharge resistors to dissipate stored energy to a safe level within a few seconds after power is removed. High-voltage capacitors are stored with the terminals shorted, as protection from potentially dangerous voltages due to dielectric absorption.

Some old, large oil-filled paper or plastic film capacitors contain polychlorinated biphenyls (PCBs). It is known that waste PCBs can leak into groundwater under landfills. Capacitors containing PCB were labelled as containing "Askarel" and several other trade names. PCB-filled paper capacitors are found in very old (pre-1975) fluorescent lamp ballasts, and other applications.

Capacitors may catastrophically fail when subjected to voltages or currents beyond their rating, or as they reach their normal end of life. Dielectric or metal interconnection failures may create arcing that vaporizes the dielectric fluid, resulting in case bulging, rupture, or even an explosion. Capacitors used in RF or sustained high-current applications can overheat, especially in the center of the capacitor rolls. Capacitors used within high-energy capacitor banks can violently explode when a short in one capacitor causes sudden dumping of energy stored in the rest of the bank into the failing unit. High voltage vacuum capacitors can generate soft X-rays even during normal operation. Proper containment, fusing, and preventive maintenance can help to minimize these hazards.

High-voltage capacitors can benefit from a pre-charge to limit in-rush currents at power-up of high voltage direct current (HVDC) circuits. This will extend the life of the component and may mitigate high-voltage hazards.

- Swollen caps of electrolytic capacitors – special design of semi-cut caps prevents capacitors from bursting
- This high-energy capacitor from a defibrillator can deliver over 500 joules of energy. A resistor is connected between the terminals for safety, to allow the stored energy to be released.
- Catastrophic failure

1.8 See also

- Capacitance meter
- Capacitor plague
- Circuit design

- Electric displacement field
- Electroluminescence
- Electronic oscillator
- Vacuum variable capacitor

1.9 References

[1] Bird, John (2010). *Electrical and Electronic Principles and Technology*. Routledge. pp. 63–76. ISBN 9780080890562. Retrieved 2013-03-17.

[2] Williams, Henry Smith. "A History of Science Volume II, Part VI: The Leyden Jar Discovered". Retrieved 2013-03-17.

[3] Keithley, Joseph F. (1999). *The Story of Electrical and Magnetic Measurements: From 500 BC to the 1940s*. John Wiley & Sons. p. 23. ISBN 9780780311930. Retrieved 2013-03-17.

[4] Houston, Edwin J. (1905). *Electricity in Every-day Life*. P. F. Collier & Son. p. 71. Retrieved 2013-03-17.

[5] Isaacson, Walter (2003). *Benjamin Franklin: An American Life*. Simon and Schuster. p. 136. ISBN 9780743260848. Retrieved 2013-03-17.

[6] Franklin, Benjamin (1749-04-29). "Experiments & Observations on Electricity: Letter IV to Peter Collinson" (PDF). p. 28. Retrieved 2009-08-09.

[7] Morse, Robert A. (September 2004). "Franklin and Electrostatics—Ben Franklin as my Lab Partner" (PDF). *Wright Center for Science Education*. Tufts University. p. 23. Retrieved 2009-08-10. After Volta's discovery of the electrochemical cell in 1800, the term was then applied to a group of electrochemical cells

[8] "eFunda: Glossary: Units: Electric Capacitance: Jar". eFunda. Retrieved 2013-03-17.

[9] "Sketch of Alessandro Volta". *The Popular Science Monthly* (New York: Bonnier Corporation): 118–119. May 1892. ISSN 0161-7370.

[10] Ulaby, p.168

[11] Ulaby, p.157

[12] Ulaby, p.169

[13] Hammond, Percy (1964). *Electromagnetism for Engineers: An Introductory Course*. The Commonwealth and International Library of Science, Technology, Engineering and Liberal Studies. Applied Electricity and Electronics Division **3**. Pergamon Press. pp. 44–45.

[14] Dorf, p.263

[15] Dorf, p.260

[16] "Capacitor charging and discharging". *All About Circuits*. Retrieved 2009-02-19.

[17] Pillai, K. P. P. (1970). "Fringing field of finite parallel-plate capacitors". *Proceedings of the Institution of Electrical Engineers* **117** (6): 1201–1204. doi:10.1049/piee.1970.0232.

[18] Ulaby, p.170

[19] Pai, S. T.; Qi Zhang (1995). *Introduction to High Power Pulse Technology*. Advanced Series in Electrical and Computer Engineering **10**. World Scientific. ISBN 9789810217143. Retrieved 2013-03-17.

[20] Dyer, Stephen A. (2004). *Wiley Survey of Instrumentation and Measurement*. John Wiley & Sons. p. 397. ISBN 9780471221654. Retrieved 2013-03-17.

[21] Scherz, Paul (2006). *Practical Electronics for Inventors* (2nd ed.). McGraw Hill Professional. p. 100. ISBN 9780071776448. Retrieved 2013-03-17.

[22] Bird, John (2007). *Electrical Circuit Theory and Technology*. Routledge. p. 501. ISBN 9780750681391. Retrieved 2013-03-17.

[23] "Ceramic Capacitor Aging Made Simple". Johanson Dielectrics. 2012-05-21. Retrieved 2013-03-17.

[24] "The Effect of Reversal on Capacitor Life" (PDF). *Engineering Bulletin 96-004*. Sorrento Electronics. November 2003. Retrieved 2013-03-17.

[25] Guinta, Steve. "Ask The Applications Engineer – 21". Analog Devices. Retrieved 2013-03-17.

[26] Kaplan, Daniel M.; White, Christopher G. *Hands-On Electronics: A Practical Introduction to Analog and Digital Circuits*. p. 19.

[27] Miller, Charles. *Illustrated Guide to the National Electrical Code*, p. 445 (Cengage Learning 2011).

[28] Alam, Mohammed; Michael H. Azarian; Michael Osterman; Michael Pecht (2010). "Effectiveness of embedded capacitors in reducing the number of surface mount capacitors for decoupling applications". *Circuit World* **36** (1): 22. doi:10.1108/03056121011015068.

1.10 Bibliography

- Dorf, Richard C.; Svoboda, James A. (2001). *Introduction to Electric Circuits* (5th ed.). New York: John Wiley & Sons. ISBN 9780471386896.
- Philosophical Transactions of the Royal Society LXXII, Appendix 8, 1782 (Volta coins the word *condenser*)
- Ulaby, Fawwaz Tayssir (1999). *Fundamentals of Applied Electromagnetics*. Upper Saddle River, New Jersey: Prentice Hall. ISBN 9780130115546.
- Zorpette, Glenn (2005). "Super Charged: A Tiny South Korean Company is Out to Make Capacitors Powerful enough to Propel the Next Generation of Hybrid-Electric Cars". *IEEE*

Spectrum (North American ed.) **42** (1): 32. doi:10.1109/MSPEC.2005.1377872.

- Deshpande, R.P. (2014). *Capacitors*. McGraw-Hill. ISBN 9780071848565.

1.11 External links

- Capacitors: Interactive Tutorial National High Magnetic Field Laboratory
- Currier, Dean P. (2000). "Adventures in Cybersound – Ewald Christian von Kleist". Archived from the original on 2008-06-25.
- "The First Condenser – A Beer Glass". SparkMuseum.
- Howstuffworks.com: How Capacitors Work
- CapSite 2015: Introduction to Capacitors
- Capacitor Tutorial – Includes how to read capacitor temperature codes
- Introduction to Capacitor and Capacitor codes
- Low ESR Capacitor Manufacturers
- How Capacitor Works – Capacitor Markings and Color Codes

Chapter 2

Types of capacitor

This article is about commercial discrete capacitors as customary components for use in electronic equipment. For the physical phenomenon, see capacitance. For the explanation of the units of measure of capacitance, see farad.

A **capacitor** (formerly known as a **condenser**, and prior to that known as a **permittor**) [1] is a passive two-terminal electrical component that stores electric energy in an electric field. The forms, styles, and materials of practical capacitors vary widely, but all contain at least two electrical conductors (called “plates”) separated by an insulating layer (called the dielectric). Capacitors are widely used as parts of electrical circuits in many common electrical devices.

Some different capacitors for electronic equipment

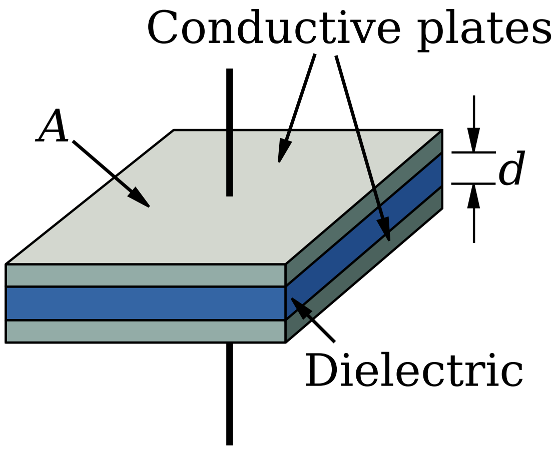
Capacitors, together with resistors, inductors, and memristors, belong to the group of "passive components" used in electronic equipment. Although, in absolute figures, the most common capacitors are integrated capacitors (e.g. in DRAMs or flash memory structures), this article is concentrated on the various styles of capacitors as discrete components.

Small capacitors are used in electronic devices to couple signals between stages of amplifiers, as components of electric filters and tuned circuits, or as parts of power supply systems to smooth rectified current. Larger capacitors are used for energy storage in such applications as strobe lights, as parts of some types of electric motors, or for power factor correction in AC power distribution systems. Standard capacitors have a fixed value of capacitance, but adjustable capacitors are frequently used in tuned circuits. Different types are used depending on required capacitance, working voltage, current handling capacity, and other properties.

2.1 General remarks

Capacitors are a good example of the fact that even the simplest device can become complicated given 250 years of evolution.[2]

2.1.1 Theory of conventional construction



A dielectric material is placed between two conducting plates (electrodes), each of area **A** *and with a separation of* **d**.

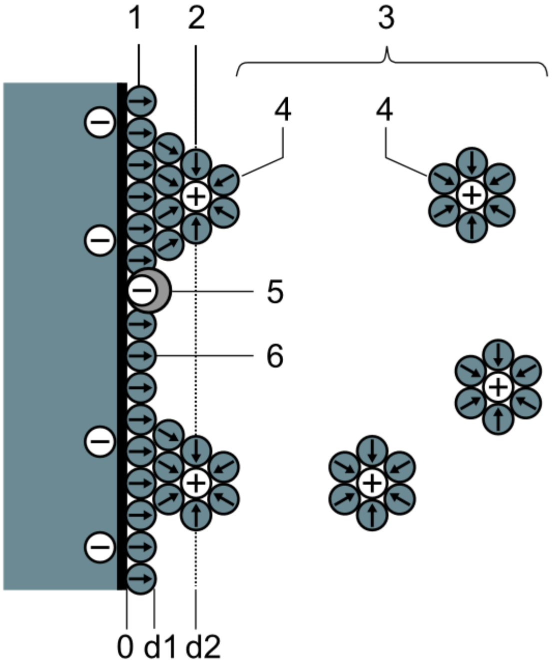
In a conventional capacitor, the electric energy is stored statically by charge separation, typically electrons, in an electric field between two electrode plates. The amount of charge stored per unit voltage is essentially a function of the size of the plates, the plate material's properties, the properties of the dielectric material placed between the plates, and the separation distance (i.e. dielectric thickness). The potential between the plates is limited by the properties of the dielectric material and the separation distance.

Nearly all conventional industrial capacitors except some special styles such as "feed-through capacitors", are constructed as "plate capacitors" even if their electrodes and the dielectric between are wound or rolled. The capacitance formula for plate capacitors is:

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

The capacitance ***C*** increases with the area ***A*** of the plates and with the permittivity ***ε*** of the dielectric material and decreases with the plate separation distance ***d***. The capacitance is therefore greatest in devices made from materials with a high permittivity, large plate area, and small distance between plates.

2.1.2 Theory of electrochemical construction



Schematic of double layer capacitor.
1. IHP Inner Helmholtz Layer
2. OHP Outer Helmholtz Layer
3. Diffuse layer
4. Solvated ions
5. Specifically adsorptive ions (Pseudocapacitance)
6. Solvent molecule.

Another type – the electrochemical capacitor – makes use of two other storage principles to store electric energy. In contrast to ceramic, film, and electrolytic capacitors, supercapacitors (also known as electrical double-layer capacitors (EDLC) or ultracapacitors) do not have a conventional dielectric. The capacitance value of an electrochemical capacitor is determined by two high-capacity storage principles. These principles are:

- electrostatic storage within Helmholtz double layers achieved on the phase interface between the surface of the electrodes and the electrolyte **(double-layer capacitance)**; and
- electrochemical storage achieved by a faradaic electron charge-transfer by specifically adsorpted ions with redox reactions **(pseudocapacitance)**. Unlike batteries, in these reactions, the ions simply cling to the atomic structure of an electrode without making or breaking chemical bonds, and no or negligibly small chemical modifications are involved in charge/discharge.

The ratio of the storage resulting from each principle can vary greatly, depending on electrode design and electrolyte composition. Pseudocapacitance can increase the capacitance value by as much as an order of magnitude over that of the double-layer by itself.[3]

2.1.3 Common capacitors and their names

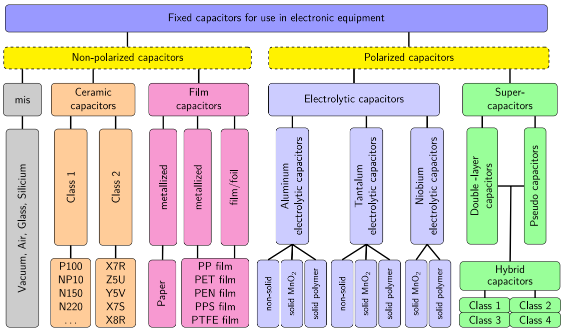
Capacitors are divided into two mechanical groups: Fixed capacitors with fixed capacitance values and variable capacitors with variable (trimmer) or adjustable (tunable) capacitance values.

The most important group is the fixed capacitors. Many got their names from the dielectric. For a systematic classification these characteristics can't be used, because one of the oldest, the electrolytic capacitor, is named instead by its cathode construction. So the most-used names are simply historical.

The most common kinds of capacitors are:

- **Ceramic capacitors** have a ceramic dielectric.
- **Film** and **paper capacitors** are named for their dielectrics.
- **Aluminum, tantalum** and **niobium electrolytic capacitors** are named after the material used as the anode and the construction of the cathode (electrolyte)
- **Polymer capacitors** are aluminum,tantalum or niobium electrolytic capacitors with conductive polymer as electrolyte
- **Supercapacitor** is the family name for:

  - **Double-layer capacitors** were named for the physical phenomenon of the Helmholtz double-layer
  - **Pseudocapacitors** were named for their ability to store electric energy electro-chemically with reversible faradaic charge-transfer
  - **Hybrid capacitors** combine double-layer and pseudocapacitors to increase power density
- **Silver mica, glass, silicon, air-gap and vacuum capacitors** are named for their dielectric.



Overview over the most commonly used fixed capacitors in electronic equipment

In addition to the above shown capacitor types, which derived their name from historical development, there are many individual capacitors that have been named based on their application. They include:

- Power capacitors, motor capacitors, DC-link capacitors, suppression capacitors, audio crossover capacitors, lighting ballast capacitors, snubber capacitors, coupling, decoupling or bypassing capacitors.

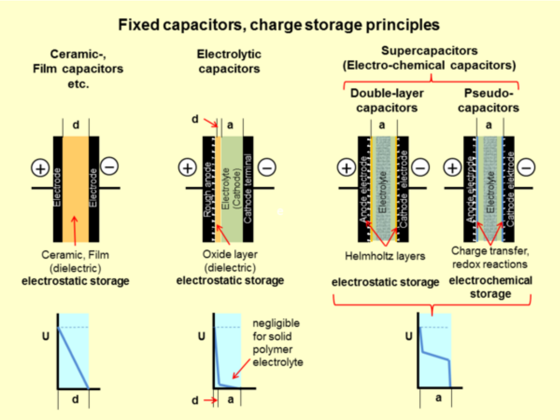
Often, more than one capacitor family is employed for these applications, e.g. interference suppression can use ceramic capacitors or film capacitors.

Other kinds of capacitors are discussed in the #Special capacitors section.

2.1.4 Dielectrics

The most common dielectrics are:

- Ceramics
- Plastic films
- Oxide layer on metal (Aluminum, Tantalum, Niobium)
- Natural materials like mica, glass, paper, air, vacuum



Principle charge storage of different capacitor types and their inherent voltage progression

All of them store their electrical charge statically within an electric field between two (parallel) electrodes.

Beneath this conventional capacitors a family of electrochemical capacitors called Supercapacitors was developed. Supercapacitors don't have a conventional dielectric. They store their electrical charge statically in Helmholtz double-layers and faradaically at the surface of electrodes

- with static Double-layer capacitance in a double-layer capacitor and
- with pseudocapacitance (faradaic charge transfer) in a Pseudocapacitor
- or with both storage principles together in hybrid capacitors.

The most important material parameters of the different dielectrics used and the appr. Helmholtz-layer thickness are given in the table below.

The capacitor's plate area can be adapted to the wanted capacitance value. The permittivity and the dielectric thickness are the determining parameter for capacitors. Ease of processing is also crucial. Thin, mechanically flexible sheets can be wrapped or stacked easily, yielding large designs with high capacitance values. Razor-thin metallized sintered ceramic layers covered with metallized electrodes however, offer the best conditions for the miniaturization of circuits with SMD styles.

A short view to the figures in the table above gives the explanation for some simple facts:

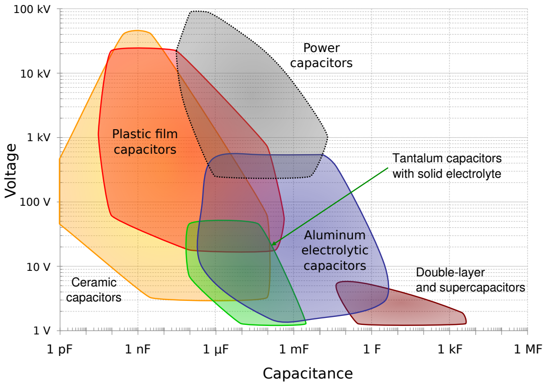
- **Supercapacitors** have the highest capacitance density because of its special charge storage principles

- **Electrolytic capacitors** have lesser capacitance density than supercapacitors but the highest capacitance density of conventional capacitors because its thin dielectric.

- **Ceramic capacitors** class 2 have much higher capacitance values in a given case than class 1 capacitors because of their much higher permittivity.

- **Film capacitors** with their different plastic film material do have a small spread in the dimensions for a given capacitance/voltage value of a film capacitor because the minimum dielectric film thickness differs between the different film materials.

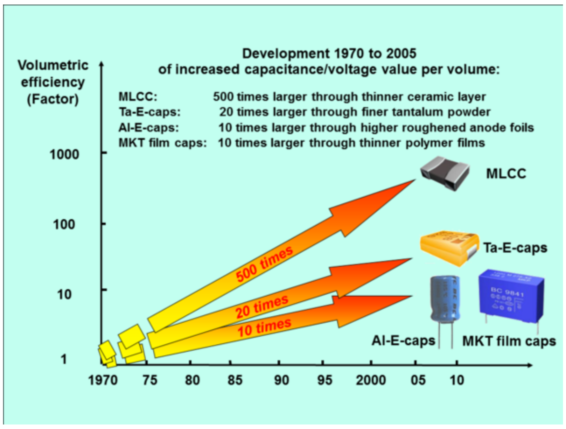
2.1.5 Capacitance and voltage range



Capacitance ranges vs. voltage ranges of different capacitor types

Capacitance ranges from picofarad to more than hundreds of farad. Voltage ratings can reach 100 kilovolts. In general, capacitance and voltage correlates with physical size and cost.

2.1.6 Miniaturization



Capacitor volumetric efficiency increased from 1970 to 2005 (click image to enlarge)

As in other areas of electronics, volumetric efficiency measures the performance of electronic function per unit volume. For capacitors, the volumetric efficiency is measured with the "CV product", calculated by multiplying the capacitance (C) by the maximum voltage rating (V), divided by the volume. From 1970 to 2005, volumetric efficiencies have improved dramatically.

- Miniaturizing of capacitors

- Stacked paper capacitor (Block capacitor) from 1923 for noise decoupling (blocking) in telegraph lines

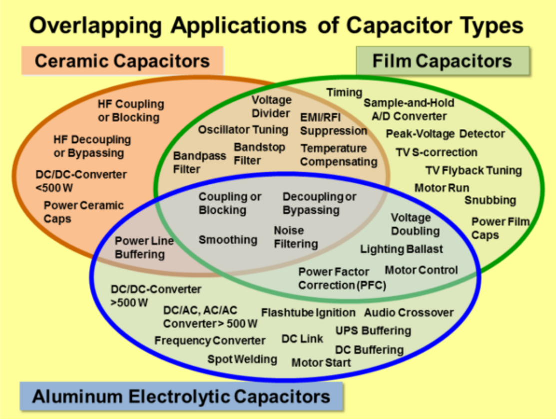
- Wound metallized paper capacitor from the early 1930s in hardpaper case, capacitance value specified in "cm" in the cgs system; 5,000 cm corresponds to 28 nF

- Folded wet aluminum electrolytic capacitor, Bell System 1929, view onto the folded anode, which was mounted in a squared housing (not shown) filled with liquid electrolyte

- Two 8 µF, 525 V wound wet aluminum electrolytic capacitors in paper housing sealed with tar out of a 1930s radio.

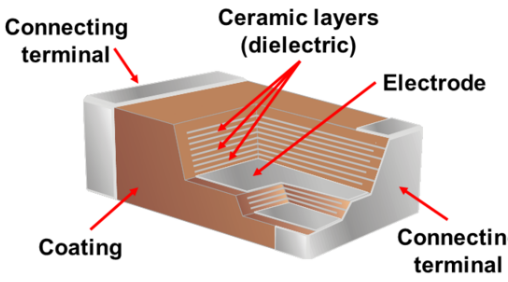
2.1.7 Overlapping range of applications

These individual capacitors can perform their application independent of their affiliation to an above shown capacitor type, so that an overlapping range of applications between the different capacitor types exists.



Comparing the three main capacitor types it shows, that a broad range of overlapping functions for many general-purpose and industrial applications exists in electronic equipment.

2.2 Types and styles



Construction of a ***M****ulti-****L****ayer* ***C****eramic* ***C****apacitor (MLCC)*

2.2.1 Ceramic capacitors

Main article: Ceramic capacitor

A **ceramic capacitor** is a non-polarized fixed capacitor made out of two or more alternating layers of ceramic and metal in which the ceramic material acts as the dielectric and the metal acts as the electrodes. The ceramic material is a mixture of finely ground granules of paraelectric or ferroelectric materials, modified by mixed oxides that are necessary to achieve the capacitor's desired characteristics. The electrical behavior of the ceramic material is divided into two stability classes:

- Class 1 ceramic capacitors with high stability and low losses compensating the influence of temperature in resonant circuit application. Common EIA/IEC code abbreviations are C0G/NP0, P2G/N150, R2G/N220, U2J/N750 etc.
- Class 2 ceramic capacitors with high volumetric efficiency for buffer, by-pass and coupling applications Common EIA/IEC code abbreviations are: X7R/2XI, Z5U/E26, Y5V/2F4, X7S/2C1, etc.

The great plasticity of ceramic raw material works well for many special applications and enables an enormous diversity of styles, shapes and great dimensional spread of ceramic capacitors. The smallest discrete capacitor, for instance, is a “01005” chip capacitor with the dimension of only 0.4 mm × 0.2 mm.

The construction of ceramic multilayer capacitors with mostly alternating layers results in single capacitors connected in parallel. This configuration increases capacitance and decreases all losses and parasitic inductances. Ceramic capacitors are well-suited for high frequencies and high current pulse loads.

Because the thickness of the ceramic dielectric layer can be easily controlled and produced by the desired application voltage, ceramic capacitors are available with rated voltages up to the 30 kV range.

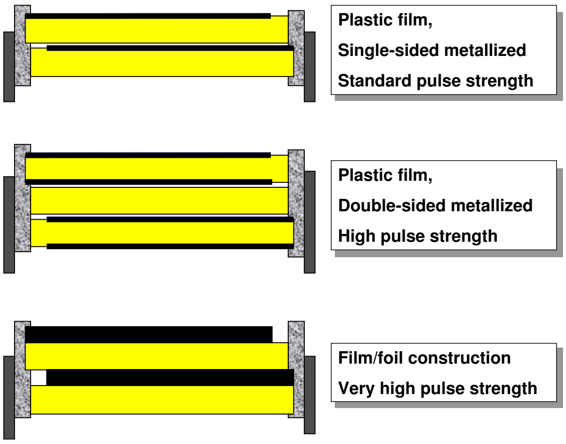
Some ceramic capacitors of special shapes and styles are used as capacitors for special applications, including RFI/EMI suppression capacitors for connection to supply mains, also known as safety capacitors,[10][11] X2Y® and three-terminal capacitors for bypassing and decoupling applications,[12][13] feed-through capacitors for noise suppression by low-pass filters[14] and ceramic power capacitors for transmitters and HF applications.[15][16]

- Diverse styles of ceramic capacitors
- Multi-layer ceramic capacitors (MLCC chips) for SMD mounting
- Ceramic X2Y® decoupling capacitors
- Ceramic EMI suppression capacitors for connection to the supply mains (safety capacitor)
- High voltage ceramic power capacitor

2.2.2 Film capacitors

Main article: Film capacitor

Film capacitors or plastic film capacitors are non-polarized capacitors with an insulating plastic film as the dielectric. The dielectric films are drawn to a thin layer, provided with metallic electrodes and wound into a cylindrical winding. The electrodes of film capacitors may be metallized aluminum or zinc, applied on one or both sides of the plastic film, resulting in metallized film capacitors or a separate metallic foil overlying the film, called film/foil capacitors.



Three examples of different film capacitor configurations for increasing surge current ratings

Metallized film capacitors offer self-healing properties. Dielectric breakdowns or shorts between the electrodes do not destroy the component. The metallized construction makes it possible to produce wound capacitors with larger capacitance values (up to 100 µF and larger) in smaller cases than within film/foil construction.

Film/foil capacitors or metal foil capacitors use two plastic films as the dielectric. Each film is covered with a thin metal foil, mostly aluminium, to form the electrodes. The advantage of this construction is the ease of connecting the metal foil electrodes, along with an excellent current pulse strength.

A key advantage of every film capacitor's internal construction is direct contact to the electrodes on both ends of the winding. This contact keeps all current paths very short. The design behaves like a large number of individual capacitors connected in parallel, thus reducing the internal ohmic losses (ESR) and ESL. The inherent geometry of film capacitor structure results in low ohmic losses and a low parasitic inductance, which makes them suitable for applications with high surge currents (snubbers) and for AC power applications, or for applications at higher frequencies.

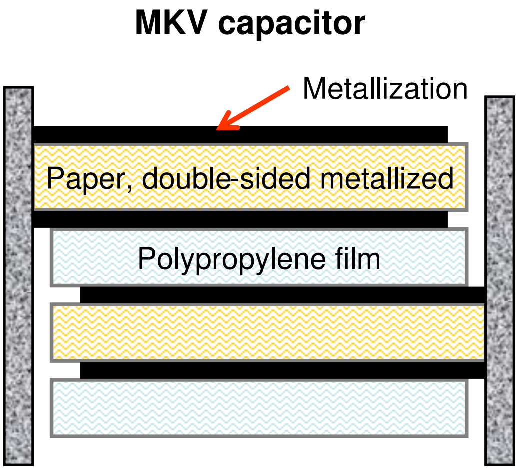
The plastic films used as the dielectric for film capacitors are Polypropylene (PP), Polyester (PET), Polyphenylene sulfide (PPS), Polyethylene naphthalate (PEN), and Polytetrafluoroethylene or Teflon (PTFE). Polypropylene film material with a market share of something about 50% and Polyester film with something about 40% are the most used film materials. The rest of something about 10% will be used by all other materials including PPS and paper with roughly 3%, each.[17][18]

Some film capacitors of special shapes and styles are used as capacitors for special applications, including RFI/EMI suppression capacitors for connection to the supply mains, also known as safety capacitors,[19] Snubber capacitors for very high surge currents,[20] Motor run capacitors, AC capacitors for motor-run applications[21]

- High pulse current load is the most important feature of film capacitors so many of the available styles do have special terminations for high currents
- Radial style (single ended) for through-hole solder mounting on printed circuit boards
- SMD style for printed circuit board surface mounting, with metallized contacts on two opposite edges
- Radial style with heavy-duty solder terminals for snubber applications and high surge pulse loads
- Heavy-duty snubber capacitor with screw terminals

2.2.3 Film power capacitors

A related type is the power film capacitor. The materials and construction techniques used for large power film capacitors mostly are similar to those of ordinary film capacitors. However, capacitors with high to very high power ratings for applications in power systems and electrical installations are often classified separately, for historical reasons. The standardization of ordinary film capacitors is oriented on electrical and mechanical parameters. The standardization of power capacitors by contrast emphasizes the safety of personnel and equipment, as given by the local regulating authority.



MKV power capacitor, double-sided metallized paper (field-free mechanical carrier of the electrodes), polypropylene film (dielectric), windings impregnated with insulating oil

As modern electronic equipment gained the capacity to handle power levels that were previously the exclusive domain of "electrical power" components, the distinction between the "electronic" and "electrical" power ratings blurred. Historically, the boundary between these two families was approximately at a reactive power of 200 volt-amps.

Film power capacitors mostly use polypropylene film as the dielectric. Other types include metallized paper capacitors (MP capacitors) and mixed dielectric film capacitors with polypropylene dielectrics. MP capacitors serve for cost applications and as field-free carrier electrodes (soggy foil capacitors) for high AC or high current pulse loads. Windings can be filled with an insulating oil or with epoxy resin to reduce air bubbles, thereby preventing short circuits.

They find use as converters to change voltage, current or frequency, to store or deliver abruptly electric energy or to improve the power factor. The rated voltage range of these capacitors is from approximately120 V AC (capacitive lighting ballasts) to 100 kV.[22]

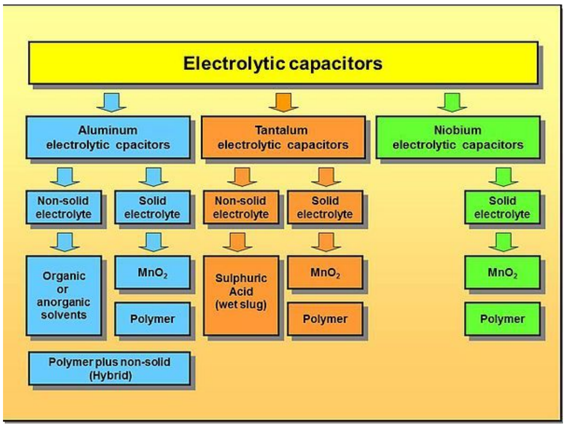
- Power film capacitors for applications in power systems, electrical installations and plants
- Power film capacitor for AC Power factor correction (PFC), packaged in a cylindrical metal can
- Power film capacitor in rectangular housing

- One of several energy storage power film capacitor banks, for magnetic field generation at the Hadron-Electron Ring Accelerator (HERA), located on the DESY site in Hamburg
- 75MVAR substation capacitor bank at 150kV

2.2.4 Electrolytic capacitors

Main article: Electrolytic capacitor

Electrolytic capacitors have a metallic anode covered with an oxidized layer used as dielectric. The second electrode is a non-solid (wet) or solid electrolyte. Electrolytic capacitors are polarized. Three families are available, categorized according to their dielectric.



Electrolytic capacitors diversification

- Aluminum electrolytic capacitors with aluminum oxide as dielectric
- Tantalum electrolytic capacitors with tantalum pentoxide as dielectric
- Niobium electrolytic capacitors with niobium pentoxide as dielectric.

The anode is highly roughened to increase the surface area. This and the relatively high permittivity of the oxide layer gives these capacitors very high capacitance per unit volume compared with film- or ceramic capacitors.

The permittivity of tantalum pentoxide is approximately three times higher than aluminium oxide, producing significantly smaller components. However, permittivity determines only the dimensions. Electrical parameters, especially conductivity, are established by the electrolyte's material and composition. Three general types of electrolytes are used:

- non solid (wet, liquid)—conductivity approximately 10 mS/cm and are the lowest cost
- solid manganese oxide—conductivity approximately 100 mS/cm offer high quality and stability
- solid conductive polymer (Polypyrrole)—conductivity approximately 10,000 mS/cm,[23] offer ESR values as low as <10 mΩ

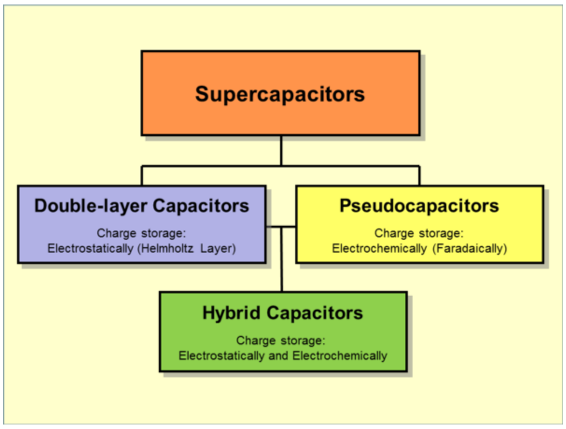
Internal losses of electrolytic capacitors, prevailing used for decoupling and buffering applications, are determined by the kind of electrolyte.

The large capacitance per unit volume of electrolytic capacitors makes them valuable in relatively high-current and low-frequency electrical circuits, e.g. in power supply filters for decoupling unwanted AC components from DC power connections or as coupling capacitors in audio amplifiers, for passing or bypassing low-frequency signals and storing large amounts of energy. The relatively high capacitance value of an electrolytic capacitor combined with the very low ESR of the polymer electrolyte of polymer capacitors, especially in SMD styles, makes them a competitor to MLC chip capacitors in personal computer power supplies.

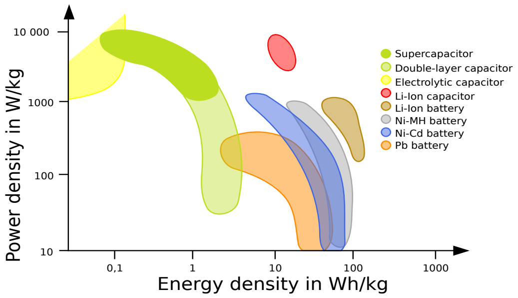
Bipolar aluminum electrolytic capacitors (also called Non-Polarized capacitors) contain two anodized aluminium foils, behaving like two capacitors connected in series opposition.

Electolytic capacitors for special applications include motor start capacitors,[24] flashlight capacitors[25] and audio frequency capacitors.[26]

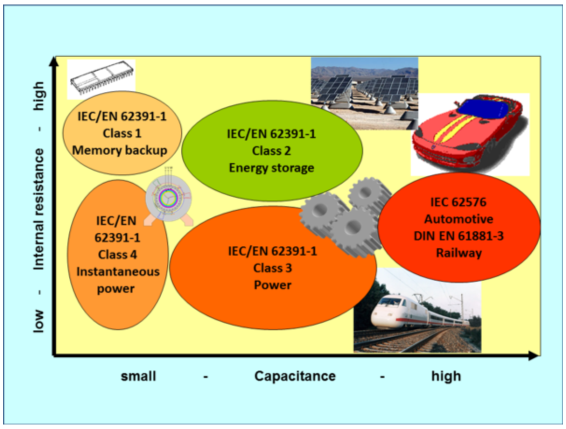
- Schematic representation
- Schematic representation of the structure of a wound aluminum electrolytic capacitor with non solid (liquid) electrolyte
- Schematic representation of the structure of a sintered tantalum electrolytic capacitor with solid electrolyte
- Aluminum, tantalum and niobium electrolytic capacitors
- Axial, radial (single ended) and V-chip styles of aluminum electrolytic capacitors
- Snap-in style of aluminum electrolytic capacitors for power applications
- SMD style for surface mounting of aluminum electrolytic capacitors with polymer electrolyte
- Tantalum electrolytic chip capacitors for surface mounting



Hierarchical classification of supercapacitors and related types



Ragone chart showing power density vs. energy density of various capacitors and batteries



Classification of supercapacitors into classes regarding to IEC 62391-1, IEC 62567and DIN EN 61881-3 standards

2.2.5 Supercapacitors

Main article: Supercapacitor

Supercapacitors (SC),[27] comprise a family of electrochemical capacitors. Supercapacitor, sometimes called **ultracapacitor** is a generic term for electric double-layer capacitors (EDLC), pseudocapacitors and hybrid capacitors. They don't have a conventional solid dielectric. The capacitance value of an electrochemical capacitor is determined by two storage principles, both of which contribute to the total capacitance of the capacitor:[28][29][30]

- Double-layer capacitance – Storage is achieved by separation of charge in a Helmholtz double layer at the interface between the surface of a conductor and an electrolytic solution. The distance of separation of charge in a double-layer is on the order of a few Angstroms (0.3–0.8 nm). This storage is electrostatic in origin.[3]
- Pseudocapacitance – Storage is achieved by redox reactions, electrosorbtion or intercalation on the surface of the electrode or by specifically adsorpted ions that results in a reversible faradaic charge-transfer. The pseudocapacitance is faradaic in origin.[3]

The ratio of the storage resulting from each principle can vary greatly, depending on electrode design and electrolyte composition. Pseudocapacitance can increase the capacitance value by as much as an order of magnitude over that of the double-layer by itself.[27]

Supercapacitors are divided into three families, based on the design of the electrodes:

- **Double-layer capacitors** – with carbon electrodes or derivates with much higher static double-layer capacitance than the faradaic pseudocapacitance
- **Pseudocapacitors** – with electrodes out of metal oxides or conducting polymers with a high amount of faradaic pseudocapacitance
- **Hybrid capacitors** – capacitors with special and asymmetric electrodes that exhibit both significant double-layer capacitance and pseudocapacitance, such as lithium-ion capacitors

Supercapacitors bridge the gap between conventional capacitors and rechargeable batteries. They have the highest available capacitance values per unit volume and the greatest energy density of all capacitors. They support up to 12,000 Farads/1.2 Volt,[31] with capacitance values up to 10,000 times that of electrolytic capacitors.[27] While existing supercapacitors have energy densities that are approximately 10% of a conventional battery, their power density is generally 10 to 100 times greater. Power density is defined as the product of energy density, multiplied by the speed at which the energy is delivered to the load. The greater power density results in much shorter charge/discharge cycles than a battery is capable, and a greater tolerance for numerous charge/discharge cycles. This makes them well-suited for parallel connection with batteries, and may improve battery performance in terms of power density.

Within electrochemical capacitors, the electrolyte is the conductive connection between the two electrodes, distinguishing them from electrolytic capacitors, in which the electrolyte only forms the cathode, the second electrode.

Supercapacitors are polarized and must operate with correct polarity. Polarity is controlled by design with asymmetric electrodes, or, for symmetric electrodes, by a potential applied during the manufacturing process.

Supercapacitors support a broad spectrum of applications for power and energy requirements, including:

- Low supply current during longer times for memory backup in (SRAMs) in electronic equipment
- Power electronics that require very short, high current, as in the KERSsystem in Formula 1 cars
- Recovery of braking energy for vehicles such as buses and trains

Supercapacitors are rarely interchangeable, especially those with higher energy densities. IEC standard 62391-1 *Fixed electric double layer capacitors for use in electronic equipment* identifies four application classes:

- Class 1, Memory backup, discharge current in mA = 1 • C (F)
- Class 2, Energy storage, discharge current in mA = 0.4 • C (F) • V (V)
- Class 3, Power, discharge current in mA = 4 • C (F) • V (V)
- Class 4, Instantaneous power, discharge current in mA = 40 • C (F) • V (V)

Exceptional for electronic components like capacitors are the manifold different trade or series names used for supercapacitors like: *APowerCap, BestCap, BoostCap, CAP-XX, DLCAP, EneCapTen, EVerCAP, DynaCap, Faradcap, GreenCap, Goldcap, HY-CAP, Kapton capacitor, Super capacitor, SuperCap, PAS Capacitor, PowerStor, PseudoCap, Ultracapacitor* making it difficult for users to classify these capacitors.

- Double-layer, Lithium-Ion and supercapacitors
- Double-layer capacitor with 1 F at 5.5 V for data buffering
- Radial (single ended) style of lithium ion capacitors for high energy density

2.2.6 Class X and Class Y capacitors

Many safety regulations mandate that Class X or Class Y capacitors must be used whenever a "fail-to-short-circuit" could put humans in danger, to guarantee galvanic isolation even when the capacitor fails.

Lightning strikes and other sources cause high voltage surges in mains power. Safety capacitors protect humans and devices from high voltage surges by shunting the surge energy to ground.[32]

In particular, safety regulations mandate a particular arrangement of Class X and Class Y mains filtering capacitors. [33]

In principle, any dielectric could be used to build Class X and Class Y capacitors; perhaps by including an internal fuse to improve safety.[34][35][36][37] In practice, capacitors that meet Class X and Class Y specifications are typically ceramic RFI/EMI suppression capacitors or plastic film RFI/EMI suppression capacitors.

2.2.7 Miscellaneous capacitors

Beneath the above described capacitors covering more or less nearly the total market of discrete capacitors some new developments or very special capacitor types as well as older types can be found in electronics.

Integrated capacitors

- Integrated capacitors—in integrated circuits, nanoscale capacitors can be formed by appropriate patterns of metallization on an isolating substrate. They may be packaged in multiple capacitor arrays with no other semiconductive parts as discrete components.[38]
- Glass capacitors—First Leyden jar capacitor was made of glass, As of 2012 glass capacitors were in use as SMD version for applications requiring ultra-reliable and ultra-stable service.

Power capacitors

- Vacuum capacitors—used in high power RF transmitters
- SF_6 gas filled capacitors—used as capacitance standard in measuring bridge circuits

Special capacitors

- Printed circuit boards—metal conductive areas in different layers of a multi-layer printed circuit board can act as a highly stable capacitor. It is common industry practice to fill unused areas of one PCB layer with the ground conductor and another layer with the power conductor, forming a large distributed capacitor between the layers.
- Wire—2 pieces of insulated wire twisted together. Capacitance values usually range from 3 pF to 15 pF. Used in homemade VHF circuits for oscillation feedback.

Specialized devices such as built-in capacitors with metal conductive areas in different layers of a multi-layer printed circuit board and kludges such as twisting together two pieces of insulated wire also exist.

Capacitors made by twisting 2 pieces of insulated wire together are called gimmick capacitors. Gimmick capacitors were used in commercial and amateur radio receivers.[39][40][41][42][43]

Obsolete capacitors

- Mica capacitors—the first capacitors with stable frequency behavior and low losses, used for military radio applications during World War II
- Air-gap capacitors—used by the first spark-gap transmitters

- Miscellaneous capacitors
- Some 1nF × 500VDC rated silver mica capacitors
- Vacuum capacitor with uranium glass encapsulation

2.2.8 Variable capacitors

Variable capacitors may have their capacitance changed by mechanical motion. Generally two versions of variable capacitors has to be to distinguished

- Tuning capacitor – variable capacitor for intentionally and repeatedly tuning an oscillator circuit in a radio or another tuned circuit
- Trimmer capacitor – small variable capacitor usually for one-time oscillator circuit internal adjustment

Variable capacitors include capacitors that use a mechanical construction to change the distance between the plates, or the amount of plate surface area which overlaps. They mostly use air as dielectric medium.

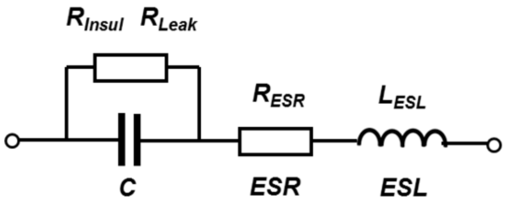
Semiconductive variable capacitance diodes are not capacitors in the sense of passive components but can change their capacitance as a function of the applied reverse bias voltage and are used like a variable capacitor. They have replaced much of the tuning and trimmer capacitors.

- Variable capacitors
- Air gap tuning capacitor
- Vacuum tuning capacitor
- Trimmer capacitor for through hole mounting
- Trimmer capacitor for surface mounting

2.3 Comparison of types

2.4 Electrical characteristics

2.4.1 Series-equivalent circuit



Series-equivalent circuit model of a capacitor

Discrete capacitors deviate from the ideal capacitor. An ideal capacitor only stores and releases electrical energy, with no dissipation. Capacitor components have losses and parasitic inductive parts. These imperfections in material and construction can have positive implications such as linear frequency and temperature behavior in class 1 ceramic capacitors. Conversely, negative implications include the non-linear, voltage-dependent capacitance in class 2 ceramic capacitors or the insufficient dielectric insulation of capacitors leading to leakage currents.

All properties can be defined and specified by a series equivalent circuit composed out of an idealized capacitance and additional electrical components which model all losses and inductive parameters of a capacitor. In this series-equivalent circuit the electrical characteristics are defined by:

- C, the capacitance of the capacitor
- R_{insul}, the insulation resistance of the dielectric, not to be confused with the insulation of the housing
- R_{leak}, the resistance representing the leakage current of the capacitor
- RESR, the equivalent series resistance which summarizes all ohmic losses of the capacitor, usually abbreviated as “ESR”
- LESL, the equivalent series inductance which is the effective self-inductance of the capacitor, usually abbreviated as “ESL”.

Using a series equivalent circuit instead of a parallel equivalent circuit is specified by IEC/EN 60384-1.

2.4.2 Standard capacitance values and tolerances

The “rated capacitance” CR or “nominal capacitance” CN is the value for which the capacitor has been designed. Actual capacitance depends on the measured frequency and ambient temperature. Standard measuring conditions are a low-voltage AC measuring method at a temperature of 20 °C with frequencies of

- 100 kHz, 1 MHz (preferred) or 10 MHz for non-electrolytic capacitors with CR ≤ 1 nF:
- 1 kHz or 10 kHz for non-electrolytic capacitors with 1 nF < CR ≤ 10 µF
- 100/120 Hz for electrolytic capacitors
- 50/60 Hz or 100/120 Hz for non-electrolytic capacitors with CR > 10 µF

For supercapacitors a voltage drop method is applied for measuring the capacitance value. .

Capacitors are available in geometrically increasing preferred values (E series standards) specified in IEC/EN 60063. According to the number of values per decade, these were called the E3, E6, E12, E24 etc. series. The range of units used to specify capacitor values has expanded to include everything from pico- (pF), nano- (nF) and microfarad (µF) to farad (F). Millifarad and kilofarad are uncommon.

The percentage of allowed deviation from the rated value is called tolerance. The actual capacitance value should be within its tolerance limits, or it is out of specification. IEC/EN 60062 specifies a letter code for each tolerance.

The required tolerance is determined by the particular application. The narrow tolerances of E24 to E96 are used for high-quality circuits such as precision oscillators and timers. General applications such as non-critical filtering or coupling circuits employ E12 or E6. Electrolytic capacitors, which are often used for filtering and bypassing capacitors mostly have a tolerance range of ±20% and need to conform to E6 (or E3) series values.

2.4.3 Temperature dependence

Capacitance typically varies with temperature. The different dielectrics express great differences in temperature sensitivity. The temperature coefficient is expressed in parts per million (ppm) per degree Celsius for class 1 ceramic capacitors or in % over the total temperature range for all others.

2.4.4 Frequency dependence

Most discrete capacitor types have more or less capacitance changes with increasing frequencies. The dielectric strength of class 2 ceramic and plastic film diminishes with rising frequency. Therefore their capacitance value decreases with increasing frequency. This phenomenon for ceramic class 2 and plastic film dielectrics is related to dielectric relaxation in which the time constant of the electrical dipoles is the reason for the frequency dependence of permittivity. The graphs below show typical frequency behavior of the capacitance for ceramic and film capacitors.

- Frequency dependence of capacitance for ceramic and film capacitors
- Frequency dependence of capacitance for ceramic class 2 capacitors (NP0 class 1 for comparisation)
- Frequency dependence of capacitance for film capacitors with different film materials

For electrolytic capacitors with non-solid electrolyte, mechanical motion of the ions occurs. Their movability is limited so that at higher frequencies not all areas of the roughened anode structure are covered with charge-carrying ions. As higher the anode structure is roughned as more the capacitance value decreases with increasing frequency. Low voltage types with highly roughened anodes display capacitance at 100 kHz approximately 10 to 20% of the value measured at 100 Hz.

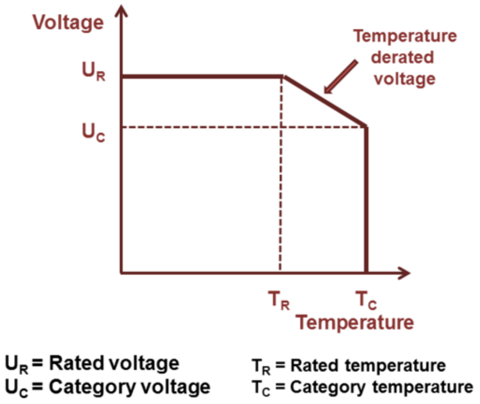
2.4.5 Voltage dependence

Capacitance may also change with applied voltage. This effect is more prevalent in class 2 ceramic capacitors. The permittivity of ferroelectric class 2 material depends on the applied voltage. Higher applied voltage lowers permittivity. The change of capacitance can drop to 80% of the value measured with the standardized measuring voltage of 0.5 or 1.0 V. This behavior is a small source of non-linearity in low-distortion filters and other analog applications. In audio applications this can be the reason for harmonic distortion.

Film capacitors and electrolytic capacitors have no significant voltage dependence.

- Voltage dependence of capacitance for some different class 2 ceramic capacitors
- Simplified diagram of the change in capacitance as a function of the applied voltage for 25-V capacitors in different kind of ceramic grades
- Simplified diagram of the change in capacitance as a function of applied voltage for X7R ceramics with different rated voltages

2.4.6 Rated and category voltage



Relation between rated and category temperature range and applied voltage

The voltage at which the dielectric becomes conductive is called the breakdown voltage, and is given by the product of the dielectric strength and the separation between the electrodes. The dielectric strength depends on temperature, frequency, shape of the electrodes, etc. Because a breakdown in a capacitor normally is a short circuit and destroys the component, the operating voltage is lower than the breakdown voltage. The operating voltage is specified such that the voltage may be applied continuously throughout the life of the capacitor.

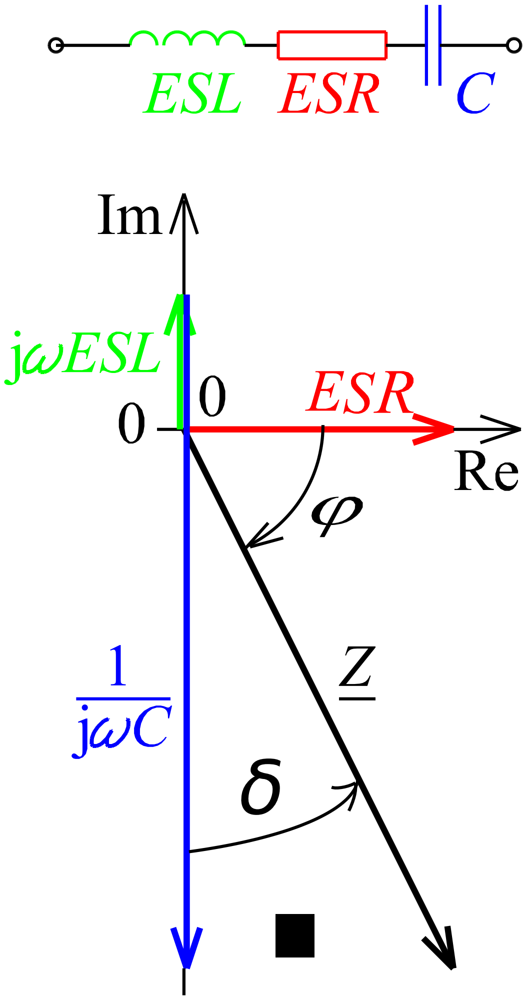
In IEC/EN 60384-1 the allowed operating voltage is called "rated voltage" or "nominal voltage". The rated voltage (UR) is the maximum DC voltage or peak pulse voltage that may be applied continuously at any temperature within the rated temperature range.

The voltage proof of nearly all capacitors decreases with increasing temperature. Some applications require a higher temperature range. Lowering the voltage applied at a higher temperature maintains safety margins. For some capacitor types therefore the IEC standard specify a second "temperature derated voltage" for a higher temperature range, the "category voltage". The category voltage (UC) is the maximum DC voltage or peak pulse voltage that may be applied continuously to a capacitor at any temperature within the category temperature range.

The relation between both voltages and temperatures is given in the picture right.

2.4.7 Impedance

In general, a capacitor is seen as a storage component for electric energy. But this is only one capacitor function. A capacitor can also act as an AC resistor. In many cases the capacitor is used as a decoupling capacitor to filter or bypass undesired biased AC frequencies to the ground. Other applications use capacitors for capacitive coupling of AC signals; the dielectric is used only for blocking DC. For such applications the AC resistance is as important as the capacitance value.



Simplified series-equivalent circuit of a capacitor for higher frequencies (above); vector diagram with electrical reactances XESL and XC and resistance ESR and for illustration the impedance Z and dissipation factor tan δ

The frequency dependent AC resistance is called impedance Z and is the complex ratio of the voltage to the current in an AC circuit. Impedance extends the concept of resistance to AC circuits and possesses both magnitude and phase at a particular frequency. This is unlike resistance, which has only magnitude.

$$Z = |Z|e^{j\theta}$$

The magnitude $|Z|$ represents the ratio of the voltage difference amplitude to the current amplitude, j is the imaginary unit, while the argument θ gives the phase difference between voltage and current.

In capacitor data sheets, only the impedance magnitude

|Z| is specified, and simply written as "Z" so that the formula for the impedance can be written in Cartesian form

$$Z = R + jX$$

where the real part of impedance is the resistance R (for capacitors ESR) and the imaginary part is the reactance X .

As shown in a capacitor's series-equivalent circuit, the real component includes an ideal capacitor C , an inductance $L(ESL)$ and a resistor $R(ESR)$. The total reactance at the angular frequency ω therefore is given by the geometric (complex) addition of a capacitive reactance (Capacitance) $X_C = -\frac{1}{\omega C}$ and an inductive reactance (Inductance): $X_L = \omega L_{\mathrm{ESL}}$.

To calculate the impedance Z the resistance has to be added geometrically and then Z is given by

$$Z = \sqrt{ESR^2 + (X_{\mathrm{C}} + (-X_{\mathrm{L}}))^2}$$

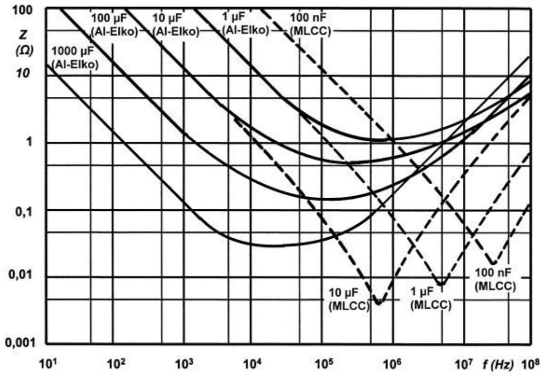
$$Z = \frac{\hat{u}}{\hat{\imath}} = \frac{U_{\mathrm{eff}}}{I_{\mathrm{eff}}}.$$

to calculate either the peak or the effective value of the current or the voltage.

In the special case of resonance, in which the both reactive resistances

$$X_C = -\frac{1}{\omega C} \text{ and } X_L = \omega L_{\mathrm{ESL}}$$

have the same value ($X_C = X_L$), then the impedance will only be determined by ESR .



Typical impedance curves for different capacitance values over frequency showing the typical form with a decreasing impedance values below resonance and increasing values above resonance. As higher the capacitance as lower the resonance.

The impedance specified in the datasheets often show typical curves for the different capacitance values. With increasing frequency as the impedance decreases down to a minimum. The lower the impedance, the more easily alternating currents can be passed through the capacitor. At the apex, the point of resonance, where XC has the same value than XL, the capacitor has the lowest impedance value. Here only the ESR determines the impedance. With frequencies above the resonance the impedance increases again due to the ESL of the capacitor. The capacitor becomes an inductance.

As shown in the graph, the higher capacitance values can fit the lower frequencies better while the lower capacitance values can fit better the higher frequencies.

Aluminum electrolytic capacitors have relatively good decoupling properties in the lower frequency range up to about 1 MHz due to their large capacitance values. This is the reason for using electrolytic capacitors in standard or switched-mode power supplies behind the rectifier for smoothing application.

Ceramic and film capacitors are already out of their smaller capacitance values suitable for higher frequencies up to several 100 MHz. They also have significantly lower parasitic inductance, making them suitable for higher frequency applications, due to their construction with end-surface contacting of the electrodes. To increase the range of frequencies, often an electrolytic capacitor is connected in parallel with a ceramic or film capacitor.[48]

Many new developments are targeted at reducing parasitic inductance (ESL). This increases the resonance frequency of the capacitor and, for example, can follow the constantly increasing switching speed of digital circuits. Miniaturization, especially in the SMD multilayer ceramic chip capacitors (MLCC), increases the resonance frequency. Parasitic inductance is further lowered by placing the electrodes on the longitudinal side of the chip instead of the lateral side. The "face-down" construction associated with multi-anode technology in tantalum electrolytic capacitors further reduced ESL. Capacitor families such as the so-called MOS capacitor or silicon capacitors offer solutions when capacitors at frequencies up to the GHz range are needed.

2.4.8 Inductance (ESL) and self-resonant frequency

ESL in industrial capacitors is mainly caused by the leads and internal connections used to connect the capacitor plates to the outside world. Large capacitors tend to have higher ESL than small ones because the distances to the plate are longer and every mm counts as an inductance.

For any discrete capacitor, there is a frequency above DC at which it ceases to behave as a pure capacitor. This frequency, where X_C is as high as X_L , is called the self-resonant frequency. The self-resonant frequency is the lowest frequency at which the impedance passes through a minimum. For any AC application the self-resonant frequency is the highest frequency at which capacitors can be used as a capacitive component.

This is critically important for decoupling high-speed logic circuits from the power supply. The decoupling capacitor supplies transient current to the chip. Without decouplers, the IC demands current faster than the connection to the power supply can supply it, as parts of the circuit rapidly switch on and off. To counter this potential problem, circuits frequently use multiple bypass capacitors—small (100 nF or less) capacitors rated for high frequencies, a large electrolytic capacitor rated for lower frequencies and occasionally, an intermediate value capacitor.

2.4.9 Ohmic losses, ESR, dissipation factor, and quality factor

The summarized losses in discrete capacitors are ohmic AC losses. DC losses are specified as "leakage current" or “insulating resistance” and are negligible for an AC specification. AC losses are non-linear, possibly depending on frequency, temperature, age or humidity. The losses result from two physical conditions:

- line losses including internal supply line resistances, the contact resistance of the electrode contact, line resistance of the electrodes, and in “wet” aluminum electrolytic capacitors and especially supercapacitors, the limited conductivity of liquid electrolytes and
- dielectric losses from dielectric polarization.

The largest share of these losses in larger capacitors is usually the frequency dependent ohmic dielectric losses. For smaller components, especially for wet electrolytic capacitors, conductivity of liquid electrolytes may exceed dielectric losses. To measure these losses, the measurement frequency must be set. Since commercially available components offer capacitance values cover 15 orders of magnitude, ranging from pF (10^{-12} F) to some 1000 F in supercapacitors, it is not possible to capture the entire range with only one frequency. IEC 60384-1 states that ohmic losses should be measured at the same frequency used to measure capacitance. These are:

- 100 kHz, 1 MHz (preferred) or 10 MHz for non-electrolytic capacitors with $C_R \le 1$ nF:
- 1 kHz or 10 kHz for non-electrolytic capacitors with 1 nF < $C_R \le 10$ µF
- 100/120 Hz for electrolytic capacitors
- 50/60 Hz or 100/120 Hz for non-electrolytic capacitors with $C_R > 10$ µF

A capacitor’s summarized resistive losses may be specified either as ESR, as a dissipation factor(DF, tan δ), or as quality factor (Q), depending on application requirements.

Capacitors with higher ripple current I_R loads, such as electrolytic capacitors, are specified with equivalent series resistance ESR. ESR can be shown as an ohmic part in the above vector diagram. ESR values are specified in datasheets per individual type.

The losses of film capacitors and some class 2 ceramic capacitors are mostly specified with the dissipation factor tan δ. These capacitors have smaller losses than electrolytic capacitors and mostly are used at higher frequencies up to some hundred MHz. However the numeric value of the dissipation factor, measured at the same frequency, is independent on the capacitance value and can be specified for a capacitor series with a range of capacitance. The dissipation factor is determined as the tangent of the reactance ($X_C - X_L$) and the ESR, and can be shown as the angle δ between imaginary and the impedance axis.

If the inductance ESL is small, the dissipation factor can be approximated as:

$$\tan\delta = ESR \cdot \omega C$$

Capacitors with very low losses, such as ceramic Class 1 and Class 2 capacitors, specify resistive losses with a quality factor (Q). Ceramic Class 1 capacitors are especially suitable for LC resonant circuits with frequencies up to the GHz range, and precise high and low pass filters. For an electrically resonant system, Q represents the effect of electrical resistance and characterizes a resonator’s bandwidth B relative to its center or resonant frequency f_0 . Q is defined as the reciprocal value of the dissipation factor.

$$Q = \frac{1}{tan\delta} = \frac{f_0}{B}$$

A high Q value is for resonant circuits a mark of the quality of the resonance.

2.4.10 Limiting current loads

A capacitor can act as an AC resistor, coupling AC voltage and AC current between two points. Every AC current flow through a capacitor generates heat inside the capacitor body. These dissipation power loss P is caused by ESR and is the squared value of the effective (RMS) current I

$$P = I^2 \cdot ESR$$

The same power loss can be written with the dissipation factor $tan\delta$ as

$$P = \frac{U^2 \cdot tan\delta}{2\pi f \cdot C}$$

The internal generated heat has to be distributed to the ambient. The temperature of the capacitor, which is established on the balance between heat produced and distributed, shall not exceed the capacitors maximum specified temperature. Hence, the ESR or dissipation factor is a mark for the maximum power (AC load, ripple current, pulse load, etc.) a capacitor is specified for.

AC currents may be a:

- ripple current—an effective (RMS) AC current, coming from an AC voltage superimposed of an DC bias, a
- pulse current—an AC peak current, coming from an voltage peak, or an
- AC current—an effective (RMS) sinusoidal current

Ripple and AC currents mainly warms the capacitor body. By this currents internal generated temperature influences the breakdown voltage of the dielectric. Higher temperature lower the voltage proof of all capacitors. In wet electrolytic capacitors higher temperatures force the evaporation of electrolytes, shortening the life time of the capacitors. In film capacitors higher temperatures may shrink the plastic film changing the capacitor's properties.

Pulse currents, especially in metallized film capacitors, heat the contact areas between end spray (schoopage) and metallized electrodes. This may reduce the contact to the electrodes, heightening the dissipation factor.

For safe operation, the maximal temperature generated by any AC current flow through the capacitor is a limiting factor, which in turn limits AC load, ripple current, pulse load, etc.

Ripple current

A "ripple current" is the RMS value of a superimposed AC current of any frequency and any waveform of the current curve for continuous operation at a specified temperature. It arises mainly in power supplies (including switched-mode power supplies) after rectifying an AC voltage and flows as charge and discharge current through the decoupling or smoothing capacitor. The "rated ripple current" shall not exceed a temperature rise of 3, 5 or 10 °C, depending on the capacitor type, at the specified maximum ambient temperature.

Ripple current generates heat within the capacitor body due to the ESR of the capacitor. The ESR, composed out of the dielectric losses caused by the changing field strength in the dielectric and the losses resulting out of the slightly resistive supply lines or the electrolyte depends on frequency and temperature. For ceramic and film capacitors in generally ESR decreases with increasing temperatures but heighten with higher frequencies due to increasing dielectric losses. For electrolytic capacitors up to roughly 1 MHz ESR decreases with increasing frequencies and temperatures.

The types of capacitors used for power applications have a specified rated value for maximum ripple current. These are primarily aluminum electrolytic capacitors, and tantalum as well as some film capacitors and Class 2 ceramic capacitors.

Aluminium electrolytic capacitors, the most common type for power supplies, experience shorter life expectancy at higher ripple currents. Exceeding the limit tends to result in explosive failure.

Tantalum electrolytic capacitors with solid manganese dioxide electrolyte are also limited by ripple current. Exceeding their ripple limits tends to shorts and burning components.

For film and ceramic capacitors, normally specified with a loss factor tan δ, the ripple current limit is determined by temperature rise in the body of approximately 10 °C. Exceeding this limit may destroy the internal structure and cause shorts.

Pulse current

The rated pulse load for a certain capacitor is limited by the rated voltage, the pulse repetition frequency, temperature range and pulse rise time. The "pulse rise time" dv/dt , represents the steepest voltage gradient of the pulse (rise or fall time) and is expressed in volts per μs (V/μs).

The rated pulse rise time is also indirectly the maximum capacity of an applicable peak current I_p . The peak current is defined as:

$$I_p = C \cdot dv/dt$$

where: I_p is in A; C in μF; dv/dt in V/μs

The permissible pulse current capacity of a metallized film capacitor generally allows an internal temperature rise of 8 to 10 K.

In the case of metallized film capacitors, pulse load depends on the properties of the dielectric material, the thickness of the metallization and the capacitor's construction, especially the construction of the contact areas between the end spray and metallized electrodes. High peak currents may lead to selective overheating of local contacts between end spray and metallized electrodes which may destroy some of the contacts, leading to increasing ESR.

For metallized film capacitors, so-called pulse tests simulate the pulse load that might occur during an application, according to a standard specification. IEC 60384 part 1, specifies that the test circuit is charged and discharged intermittently. The test voltage corresponds to the rated DC voltage and the test comprises 10000 pulses with a repetition frequency of 1 Hz. The pulse stress capacity is the pulse rise time. The rated pulse rise time is specified as 1/10 of the test pulse rise time.

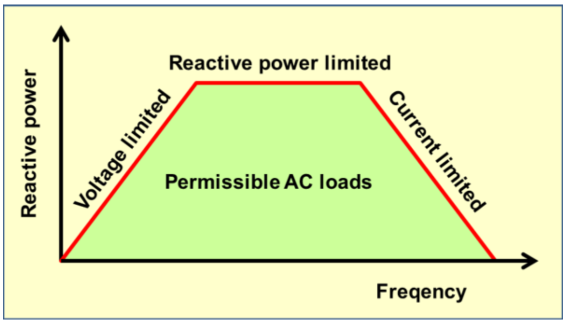
The pulse load must be calculated for each application. A general rule for calculating the power handling of film capacitors is not available because of vendor-related internal construction details. To prevent the capacitor from overheating the following operating parameters have to be considered:

- peak current per µF
- Pulse rise or fall time dv/dt in V/µs
- relative duration of charge and discharge periods (pulse shape)
- maximum pulse voltage (peak voltage)
- peak reverse voltage;
- Repetition frequency of the pulse
- Ambient temperature
- Heat dissipation (cooling)

Higher pulse rise times are permitted for pulse voltage lower than the rated voltage.

Examples for calculations of individual pulse loads are given by many manufactures, e.g. WIMA[52] and Kemet.[53]

AC current

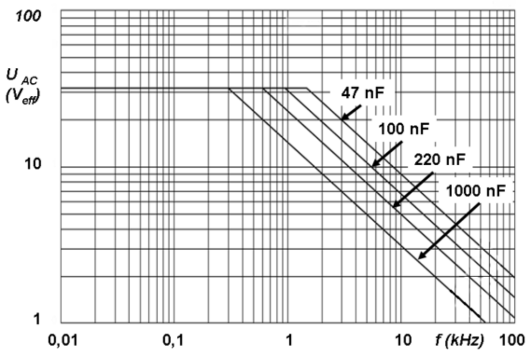


Limiting conditions for capacitors operating with AC loads

An AC load only can be applied to a non-polarized capacitor. Capacitors for AC applications are primarily film capacitors, metallized paper capacitors, ceramic capacitors and bipolar electrolytic capacitors.

The rated AC load for an AC capacitor is the maximum sinusoidal effective AC current (rms) which may be applied continuously to a capacitor within the specified temperature range. In the datasheets the AC load may be expressed as

- rated AC voltage at low frequencies,
- rated reactive power at intermediate frequencies,
- reduced AC voltage or rated AC current at high frequencies.



Typical rms AC voltage curves as a function of frequency, for 4 different capacitance values of a 63 V DC film capacitor series

The rated AC voltage for film capacitors is generally calculated so that an internal temperature rise of 8 to 10 °K is the allowed limit for safe operation. Because dielectric losses increase with increasing frequency, the specified AC voltage has to be derated at higher frequencies. Datasheets for film capacitors specify special curves for derating AC voltages at higher frequencies.

If film capacitors or ceramic capacitors only have a DC specification, the peak value of the AC voltage applied has to be lower than the specified DC voltage.

AC loads can occur in AC motor run capacitors, for voltage doubling, in snubbers, lighting ballast and for power factor correction PFC for phase shifting to improve transmission network stability and efficiency, which is one of the most important applications for large power capacitors. These mostly large PP film or metallized paper capacitors are limited by the rated reactive power VAr.

Bipolar electrolytic capacitors, to which an AC voltage may be applicable, are specified with a rated ripple current.

2.4.11 Insulation resistance and self-discharge constant

The resistance of the dielectric is finite, leading to some level of DC "leakage current" that causes a charged capacitor to lose charge over time. For ceramic and film capacitors, this resistance is called “insulation resistance R$_\mathrm{ins}$". This resistance is represented by the resistor R$_\mathrm{ins}$ in parallel with the capacitor in the series-equivalent circuit of capacitors. Insulation resistance must not be confused with the outer isolation of the component with respect to the environment.

The time curve of self-discharge over insulation resistance with decreasing capacitor voltage follows the formula

$$u(t) = U_0 \cdot \mathrm{e}^{-t/\tau_\mathrm{s}},$$

With stored DC voltage U_0 and self-discharge constant

$$\tau_\mathrm{s} = R_\mathrm{ins} \cdot C$$

Thus, after τ_s voltage U_0 drops to 37% of the initial value.

The self-discharge constant is an important parameter for the insulation of the dielectric between the electrodes of ceramic and film capacitors. For example, a capacitor can be used as the time-determining component for time relays or for storing a voltage value as in a sample and hold circuits or operational amplifiers.

Class 1 ceramic capacitors have an insulation resistance of at least 10 GΩ, while class 2 capacitors have at least 4 GΩ or a self-discharge constant of at least 100 s. Plastic film capacitors typically have an insulation resistance of 6 to 12 GΩ. This corresponds to capacitors in the uF range of a self-discharge constant of about 2000–4000 s.[54]

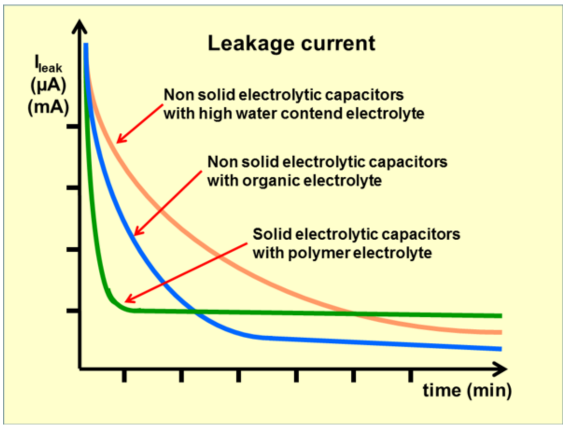
Insulation resistance respectively the self-discharge constant can be reduced if humidity penetrates into the winding. It is partially strongly temperature dependent and decreases with increasing temperature. Both decrease with increasing temperature.

In electrolytic capacitors, the insulation resistance is defined as leakage current.

2.4.12 Leakage current

For electrolytic capacitors the insulation resistance of the dielectric is termed “leakage current”. This DC current is represented by the resistor R$_\mathrm{leak}$ in parallel with the capacitor in the series-equivalent circuit of electrolytic capacitors. This resistance between the terminals of a capacitor is also finite. R$_\mathrm{leak}$ is lower for electrolytics than for ceramic or film capacitors.

The leakage current includes all weak imperfections of the dielectric caused by unwanted chemical processes and mechanical damage. It is also the DC current that can pass through the dielectric after applying a voltage. It depends on the interval without voltage applied (storage time), the thermic stress from soldering, on voltage applied, on temperature of the capacitor, and on measuring time.



The general leakage current behavior of electrolytic capacitors depend on the kind of electrolyte

The leakage current drops in the first minutes after applying DC voltage. In this period the dielectric oxide layer can self-repair weaknesses by building up new layers. The time required depends generally on the electrolyte. Solid electrolytes drop faster than non-solid electrolytes but remain at a slightly higher level.

The leakage current in non-solid electrolytic capacitors as well as in manganese oxide solid tantalum capacitors decreases with voltage-connected time due to self-healing effects. Although electrolytics leakage current is higher than current flow over insulation resistance in ceramic or film capacitors, the self-discharge of modern non solid electrolytic capacitors takes several weeks.

A particular problem with electrolytic capacitors is storage time. Higher leakage current can be the result of longer storage times. These behaviors are limited to electrolytes with a high percentage of water. Organic solvents such as GBL do not have high leakage with longer storage times.

Leakage current is normally measured 2 or 5 minutes after applying rated voltage.

2.4.13 Microphonics

All ferroelectric materials exhibit piezoelectricity a piezoelectric effect. Because Class 2 ceramic capacitors use ferroelectric ceramics dielectric, these types of capacitors may have electrical effects called microphonics. Microphonics (microphony) describes how electronic components transform mechanical vibrations into an undesired electrical signal (noise).[55] The dielectric may absorb mechanical forces from shock or vibration by changing thickness and changing the electrode separation, affecting the capacitance, which in turn induces an AC current. The resulting interference is especially problematic in audio applications, potentially causing feedback or unintended recording.

In the reverse microphonic effect, varying the electric field between the capacitor plates exerts a physical force, turning them into an audio speaker. High current impulse loads or high ripple currents can generate audible sound from the capacitor itself, draining energy and stressing the dielectric.[56]

2.4.14 Dielectric absorption (soakage)

Main article: Dielectric absorption

Dielectric absorption occurs when a capacitor that has remained charged for a long time discharges only incompletely when briefly discharged. Although an ideal capacitor would reach zero volts after discharge, real capacitors develop a small voltage from time-delayed dipole discharging, a phenomenon that is also called dielectric relaxation, “soakage” or “battery action”.

In many applications of capacitors dielectric absorption is not a problem but in some applications, such as long-time-constant integrators, sample-and-hold circuits, switched-capacitor analog-to-digital converters, and very low-distortion filters, the capacitor must not recover a residual charge after full discharge, so capacitors with low absorption are specified.[59] The voltage at the terminals generated by the dielectric absorption may in some cases possibly cause problems in the function of an electronic circuit or can be a safety risk to personnel. In order to prevent shocks most very large capacitors are shipped with shorting wires that need to be removed before they are used.[60]

2.4.15 Energy density

The capacitance value depends on the dielectric material (ε), the surface of the electrodes (A) and the distance (d) separating the electrodes and is given by the formula of a plate capacitor:

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

The separation of the electrodes and the voltage proof of the dielectric material defines the breakdown voltage of the capacitor. The breakdown voltage is proportional to the thickness of the dielectric.

Theoretically, given two capacitors with the same mechanical dimensions and dielectric, but one of them have half the thickness of the dielectric. With the same dimensions this one could place twice the parallel-plate area inside. This capacitor has theoretically 4 times the capacitance as the first capacitor but half of the voltage proof.

Since the energy density stored in a capacitor is given by:

$$E_{\text{stored}} = \frac{1}{2} C V^2,$$

thus a capacitor having a dielectric half as thick as another has 4 times higher capacitance but ½ voltage proof, yielding an equal maximum energy density.

Therefore, dielectric thickness does not affect energy density within a capacitor of fixed overall dimensions. Using a few thick layers of dielectric can support a high voltage, but low capacitance, while thin layers of dielectric produce a low breakdown voltage, but a higher capacitance.

This assumes that neither the electrode surfaces nor the permittivity of the dielectric change with the voltage proof. A simple comparison with two existing capacitor series can show whether reality matches theory. The comparison is easy, because the manufacturers use standardized case sizes or boxes for different capacitance/voltage values within a series.

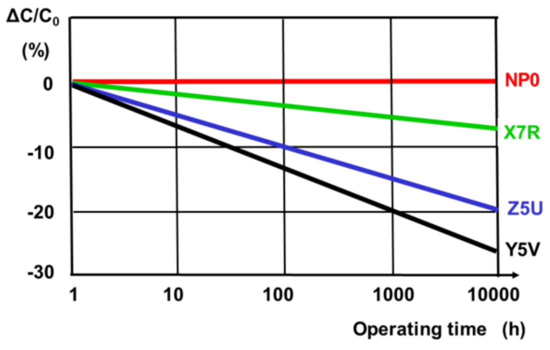
In reality modern capacitor series do not fit the theory. For electrolytic capacitors the sponge-like rough surface of the anode foil gets smoother with higher voltages, decreasing the surface area of the anode. But because the energy increases squared with the voltage, and the surface of the anode decreases lesser than the voltage proof, the energy density increases clearly. For film capacitors the permittivity changes with dielectric thickness and other mechanical parameters so that the deviation from the theory has other reasons.[63]

Comparing the capacitors from the table with a supercapacitor, the highest energy density capacitor family. For this, the capacitor 25 F/2.3 V in dimensions D × H = 16 mm × 26 mm from Maxwell HC Series, compared with the electrolytic capacitor of approximately equal size in the table. This supercapacitor has roughly 5000 times higher capacitance than the 4700/10 electrolytic capacitor but ¼ of the voltage and has about 66,000 mWs (0.018 Wh) stored electrical energy,[64] approximately 100 times higher energy density (40 to 280 times) than the electrolytic capacitor.

2.4.16 Long time behavior, aging

Electrical parameters of capacitors may change over time during storage and application. The reasons for parameter changings are different, it may be a property of the dielectric, environmental influences, chemical processes or drying-out effects for non-solid materials.

Aging



Aging of different Class 2 ceramic capacitors compared with NP0-Class 1 ceramic capacitor

In ferroelectric Class 2 ceramic capacitors, capacitance decreases over time. This behavior is called “aging”. This aging occurs in ferroelectric dielectrics, where domains of polarization in the dielectric contribute to the total polarization. Degradation of polarized domains in the dielectric decreases permittivity and therefore capacitance over time.[65][66] The aging follows a logarithmic law. This defines the decrease of capacitance as constant percentage for a time decade after the soldering recovery time at a defined temperature, for example, in the period from 1 to 10 hours at 20 °C. As the law is logarithmic, the percentage loss of capacitance will twice between 1 h and 100 h and 3 times between 1 h and 1,000 h and so on. Aging is fastest near the beginning, and the absolute capacitance value stabilizes over time.

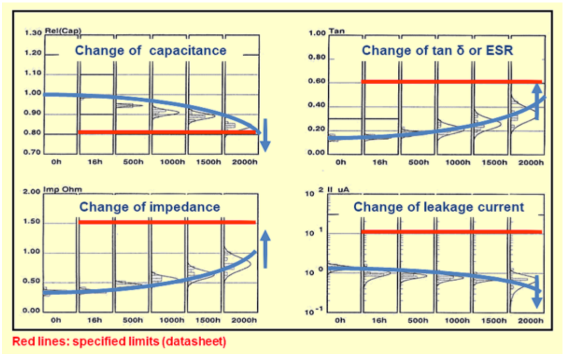
The rate of aging of Class 2 ceramic capacitors depends mainly on its materials. Generally, the higher the temperature dependence of the ceramic, the higher the aging percentage. The typical aging of X7R ceramic capacitors is about 2.5&nbs;% per decade.[67] The aging rate of Z5U ceramic capacitors is significantly higher and can be up to 7% per decade.

The aging process of Class 2 ceramic capacitors may be reversed by heating the component above the Curie point.

Class 1 ceramic capacitors and film capacitors do not have ferroelectric-related aging. Environmental influences such as higher temperature, high humidity and mechanical stress can, over a longer period, lead to a small irreversible change in the capacitance value sometimes called aging, too.

The change of capacitance for P 100 and N 470 Class 1 ceramic capacitors is lower than 1%, for capacitors with N 750 to N 1500 ceramics it is ≤ 2%. Film capacitors may lose capacitance due to self-healing processes or gain it due to humidity influences. Typical changes over 2 years at 40 °C are, for example, ±3% for PE film capacitors and ±1% PP film capacitors.

Life time



The electrical values of electrolytic capacitors with non-solid electrolyte changes over the time due to evaporation of electrolyte. Reaching specified limits of the parameters the capacitors will be count as “wear out failure”.

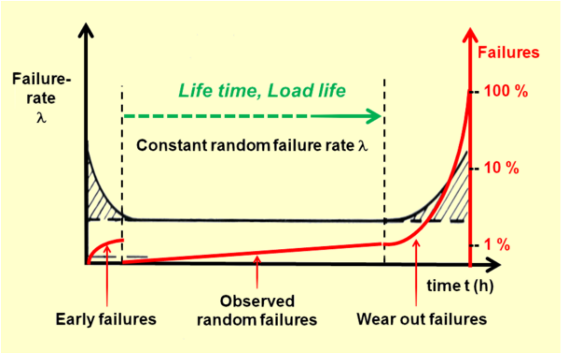
Electrolytic capacitors with non-solid electrolyte age as the electrolyte evaporates. This evaporation depends on temperature and the current load the capacitors experience. Electrolyte escape influences capacitance and ESR. Capacitance decreases and the ESR increases over time. In contrast to ceramic, film and electrolytic capacitors with solid electrolytes, “wet” electrolytic capacitors reach a specified “end of life” reaching a specified maximum change of capacitance or ESR. End of life, “load life” or “lifetime” can be estimated either by formula or diagrams[68] or roughly by a so-called “10-degree-law”. A typical specification for an electrolytic capacitor states a lifetime of 2,000 hours at 85 °C, doubling for every 10 degrees lower temperature, achieving lifespan of approximately 15 years at room temperature.

Supercapacitors also experience electrolyte evaporation over time. Estimation is similar to wet electrolytic capacitors. Additional to temperature the voltage and current load influence the life time. Lower voltage than rated voltage and lower current loads as well as lower temperature extend the life time.

2.4.17 Failure rate

Capacitors are reliable components with low failure rates, achieving life expectancies of decades under normal conditions. Most capacitors pass a test at the end of production similar to a "burn in", so that early failures are found during production, reducing the number of post-shipment failures.

Reliability for capacitors is usually specified in numbers of Failures In Time (FIT) during the period of constant random failures. FIT is the number of failures that can be expected in one billion (10^9) component-hours of operation at fixed working conditions (e.g. 1000 devices for 1 million hours, or 1 million devices for 1000 hours each, at 40 °C and 0.5 UR). For other conditions of applied voltage, current load, temperature, mechanical influences and



The life time (load life) of capacitors correspondents with the time of constant random failure rate shown in the bathtub curve. For electrolytic capacitors with non-solid electrolyte and supercapacitors ends this time with the beginning of wear out failures due to evaporation of electrolyte

humidity the FIT can recalculated with terms standardized for industrial[69] or military[70] contexts.

2.5 Additional information

2.5.1 Soldering

Capacitors may experience changes to electrical parameters due to environmental influences like soldering, mechanical stress factors (vibration, shock) and humidity. The greatest stress factor is soldering. The heat of the solder bath, especially for SMD capacitors, can cause ceramic capacitors to change contact resistance between terminals and electrodes; in film capacitors, the film may shrink, and in wet electrolytic capacitors the electrolyte may boil. A recovery period enables characteristics to stabilize after soldering; some types may require up to 24 hours. Some properties may change irreversibly by a few per cent from soldering.

2.5.2 Electrolytic behavior from storage or disuse

Electrolytic capacitors with non-solid electrolyte are "aged" during manufacturing by applying rated voltage at high temperature for a sufficient time to repair all cracks and weaknesses that may have occurred during production. Some electrolytes with a high water content react quite aggressively or even violently with unprotected aluminum. This leads to a "storage" or "disuse" problem of electrolytic capacitors manufactured before the 1980s. Chemical processes weaken the oxide layer when these capacitors are not used for too long. New electrolytes with "inhibitors" or "passivators" were developed during the 1980s to solve this problem.[71][72] As of 2012 the standard storage time for electronic components of two years at room temperature substantiates (cased) by the oxidation of the terminals will be specified for electrolytic capacitors with non-solid electrolytes, too. Special series for 125 °C with organic solvents like GBL are specified up to 10 years storage time ensure without pre-condition the proper electrical behavior of the capacitors.[73]

For antique radio equipment, "pre-conditioning" of older electrolytic capacitors may be recommended. This involves applying the operating voltage for some 10 minutes over a current limiting resistor to the terminals of the capacitor. Applying a voltage through a safety resistor repairs the oxide layers.

2.5.3 IEC/EN standards

The tests and requirements to be met by capacitors for use in electronic equipment for approval as standardized types are set out in the generic specification IEC/EN 60384-1 in the following sections.[74]

Generic specification

- IEC/EN 60384-1 - *Fixed capacitors for use in electronic equipment*

Ceramic capacitors

- IEC/EN 60384-8—*Fixed capacitors of ceramic dielectric, Class 1*
- IEC/EN 60384-9—*Fixed capacitors of ceramic dielectric, Class 2*
- IEC/EN 60384-21—*Fixed surface mount multilayer capacitors of ceramic dielectric, Class 1*
- IEC/EN 60384-22—*Fixed surface mount multilayer capacitors of ceramic dielectric, Class 2*

Film capacitors

- IEC/EN 60384-2—*Fixed metallized polyethylene-terephthalate film dielectric d.c. capacitors*
- IEC/EN 60384-11—*Fixed polyethylene-terephthalate film dielectric metal foil d.c. capacitors*
- IEC/EN 60384-13—*Fixed polypropylene film dielectric metal foil d.c. capacitors*
- IEC/EN 60384-16—*Fixed metallized polypropylene film dielectric d.c. capacitors*
- IEC/EN 60384-17—*Fixed metallized polypropylene film dielectric a.c. and pulse*
- IEC/EN 60384-19—*Fixed metallized polyethylene-terephthalate film dielectric surface mount d.c. capacitors*

- IEC/EN 60384-20—*Fixed metalized polyphenylene sulfide film dielectric surface mount d.c. capacitors*
- IEC/EN 60384-23—*Fixed metallized polyethylene naphthalate film dielectric chip d.c. capacitors*

Electrolytic capacitors

- IEC/EN 60384-3—*Surface mount fixed tantalum electrolytic capacitors with manganese dioxide solid electro*lyte
- IEC/EN 60384-4—*Aluminium electrolytic capacitors with solid (MnO2) and non-solid electrolyte*
- IEC/EN 60384-15—*fixed tantalum capacitors with non-solid and solid electrolyte*
- IEC/EN 60384-18—*Fixed aluminium electrolytic surface mount capacitors with solid (MnO_2) and non-solid electrolyte*
- IEC/EN 60384-24—*Surface mount fixed tantalum electrolytic capacitors with conductive polymer solid electrolyte*
- IEC/EN 60384-25—*Surface mount fixed aluminium electrolytic capacitors with conductive polymer solid electrolyte*
- IEC/EN 60384-26-*Fixed aluminium electrolytic capacitors with conductive polymer solid electrolyte*

Supercapacitors

- IEC/EN 62391-1—*Fixed electric double-layer capacitors for use in electric and electronic equipment - Part 1: Generic specification*
- IEC/EN 62391-2—*Fixed electric double-layer capacitors for use in electronic equipment - Part 2: Sectional specification - Electric double-layer capacitors for power application*

2.5.4 Capacitor symbols

Capacitor symbols

2.5.5 Markings

Imprinted

Capacitors, like most other electronic components and if enough space is available, have imprinted markings to indicate manufacturer, type, electrical and thermal characteristics, and date of manufacture. If they are large enough the capacitor is marked with:

- manufacturer's name or trademark;
- manufacturer's type designation;
- polarity of the terminations (for polarized capacitors)
- rated capacitance;
- tolerance on rated capacitance
- rated voltage and nature of supply (AC or DC)
- climatic category or rated temperature;
- year and month (or week) of manufacture;
- certification marks of safety standards (for safety EMI/RFI suppression capacitors)

Polarized capacitors have polarity markings, usually "−" (minus) sign on the side of the negative electrode for electrolytic capacitors or a stripe or "+" (plus) sign, see #Polarity marking. Also, the negative lead for leaded "wet" e-caps is usually shorter.

Smaller capacitors use a shorthand notation. The most commonly used format is: XYZ J/K/M VOLTS V, where XYZ represents the capacitance (calculated as XY × 10^Z pF), the letters J, K or M indicate the tolerance (±5%, ±10% and ±20% respectively) and VOLTS V represents the working voltage.

Examples:

- 105K 330V implies a capacitance of 10×10^5 pF = 1 µF (K = ±10%) with a working voltage of 330 V.
- 473M 100V implies a capacitance of 47×10^3 pF = 47 nF (M = ±20%) with a working voltage of 100 V.

Capacitance, tolerance and date of manufacture can be indicated with a short code specified in IEC/EN 60062. Examples of short-marking of the rated capacitance (microfarads): µ47 = 0,47 µF, 4µ7 = 4,7 µF, 47µ = 47 µF

The date of manufacture is often printed in accordance with international standards.

- Version 1: coding with year/week numeral code, "1208" is "2012, week number 8".
- Version 2: coding with year code/month code. The year codes are: "R" = 2003, "S"= 2004, "T" = 2005, "U" = 2006, "V" = 2007, "W" = 2008, "X" = 2009, "A" = 2010, "B" = 2011, "C" = 2012, "D" = 2013, etc. Month codes are: "1" to "9" = Jan. to Sept., "O" = October, "N" = November, "D" = December. "X5" is then "2009, May"

For very small capacitors like MLCC chips no marking is possible. Here only the traceability of the manufacturers can ensure the identification of a type.

Colour coding

Main article: Electronic color code

As of 2013 Capacitors do not use color coding.

2.5.6 Polarity marking

- Polarity marking
-
-
-

Aluminum e-caps with non-solid electrolyte have a polarity marking at the cathode (minus) side. Aluminum, tantalum, and niobium e-caps with solid electrolyte have a polarity marking at the anode (plus) side. Supercapacitor are marked at the minus side.

2.6 Market segments

Discrete capacitors today are industrial products produced in very large quantities for use in electronic and in electrical equipment. Globally, the market for fixed capacitors was estimated at approximately US$18 billion in 2008 for 1,400 billion (1.4 × 10^{12}) pieces.[75] This market is dominated by ceramic capacitors with estimate of approximately one trillion (1 × 10^{12}) items per year.[2]

Detailed estimated figures in value for the main capacitor families are:

- Ceramic capacitors—US$8.3 billion (46%);
- Aluminum electrolytic capacitors—US$3.9 billion (22%);
- Film capacitors and Paper capacitors—US$2.6 billion, (15%);
- Tantalum electrolytic capacitors—US$2.2 billion (12%);
- Super capacitors (Double-layer capacitors)—US$0.3 billion (2%); and
- Others like silver mica and vacuum capacitors—US$0.7 billion (3%).

All other capacitor types are negligible in terms of value and quantity compared with the above types.

2.7 See also

- Circuit design
- Tantalum capacitor

2.8 References

[1] Terrell Croft "Library of Practical Electricity"(1917)

[2] J. Ho, T. R. Jow, S. Boggs, Historical Introduction to Capacitor Technology

[3] Adam Marcus Namisnyk (23 June 2003). "A Survey of Electrochemical Supercapacitor Technology". Retrieved 2011-06-24.

[4] WIMA, Characteristics of Metallized Film Capacitors in Comparison with Other Dielectrics

[5] Film Capacitors, TDK Epcos, General technical information

[6] AVX, Dielectric Comparison Chart

[7] Holystone, Capacitor Dielectric Comparison, Technical Note 3

[8] P. Bettacchi, D. Montanari, D. Zanarini, D. Orioli, G. Rondelli, A. Sanua, KEMET Electronics Power Film Capacitors for Industrial Applications

[9] S. P. Murarka, Moshe Eizenberg, A. K. Sinha (2003) (in German), *Interlayer dielectrics for semiconductor technologies*, Academic Press, pp. 338–339, ISBN 9780125112215

[10] General technical information of (RFI/EMI)Noise suppression capacitors on AC mains

[11] Vishay, Capacitors - RFI Class X/Y

[12] X2Y® Technology

[13] Three-terminal Capacitor Structure, Murata

[14] Murata, Three-terminal Capacitor Structure, No.TE04EA-1.pdf 98.3.20

[15] Vishay, Ceramic RF-Power Capacitors

[16] Vishay. "Capacitors - RF Power". Vishay. Retrieved 2013-03-09.

[17] Passive component magazine, Nov./Dec. 2005, F. Jacobs, p. 29 ff Polypropylene Capacitor Film Resin

[18] "Capacitor Reports | Resistor Reports | Electronic Analysis | Dennis Zogbi | Paumanok Publications". Paumanokgroup.com. 2013-11-08. Retrieved 2014-03-02.

[19] WIMA, RFI Capacitors

[20] WIMA Snubber Capacitors

[21] Amrad Engineering Inc., Motor run capacitors

[22] Epcos, Capacitors for power electronics, General technical information

[23] Sanyo, Capacitor lecture POSCAP (Ta) (Basic), Polymerized electrolyte

[24] CDE, Motor Start Capacitors

[25] Rubycon, Aluminum Electrolytic Capacitors for Strobe Flash

[26] Fischer & Tausche, Electrolytic capacitor for audio frequency

[27] B. E. Conway (1999). *Electrochemical Supercapacitors: Scientific Fundamentals and Technological Applications*. Berlin: Springer. ISBN 0306457369. Retrieved November 21, 2014. see also Brian E. Conway in Electrochemistry Encyclopedia: *Electrochemical Capacitors — Their Nature, Function and Applications*

[28] Marin S. Halper, James C. Ellenbogen (March 2006). *Supercapacitors: A Brief Overview* (Technical report). MITRE Nanosystems Group. Retrieved 2013-04-02.

[29] Elzbieta Frackowiak, Francois Beguin, PERGAMON, Carbon 39 (2001) 937–950, Carbon materials for the electrochemical storage of energy in Capacitors

[30] Yu.M. Volfkovich, A.A. Mikhailin, D.A. Bograchev, V.E. Sosenkin and V.S. Bagotsky, Studies of Supercapacitor Carbon Electrodes with High Pseudocapacitance, A. N. Frumkin Institute of Physical Chemistry and Electrochemistry, Russian Academy of Sciences, Moscow, Russia, Dr. Ujjal Kumar Sur (Ed.), ISBN 978-953-307-830-4

[31] Elton

[32] "AC Safety Capacitors".

[33] "Across-the-line Capacitors, Antenna-coupling Components, Line-bypass Components and Fixed Capacitors for Use in Electronic Equipment". UL Online Certification Directory.

[34] Douglas Edson and David Wadler. "A New Low ESR Fused Solid Tantalum Capacitor".

[35] DeMatos, H. "Design of an Internal Fuse for a High-Frequency Solid Tantalum Capacitor". 1980. doi: 10.1109/TCHMT.1980.1135610

[36] Tagare. "Electrical Power Capacitors". 2001.

[37] Hemant Joshi. "Residential, Commercial and Industrial Electrical Systems: Equipment and selection". 2008. section 21.2.1: "Internal fuse". p. 446.

[38] IPDiA, 3D Silicon Capacitors

[39] Harry Lythall - SM0VPO. "Gimmick Capacitors".

[40] Darren Ashby, Bonnie Baker, Ian Hickman, Walt Kester, Robert Pease, Tim Williams, Bob Zeidman. "Circuit Design: Know It All". 2011. p. 201.

[41] Robert A. Pease. "Troubleshooting Analog Circuits". 1991. p. 20.

[42] Robert A. Pease. "Troubleshooting analog circuits, part 2: The right equipment is essential for effective troubleshooting". EDN January 19, 1989. p. 163.

[43] David Cripe NM0S and Four State QRP Group. "Instruction Manual Cyclone 40: 40 Meter Transceiver". 2013. p. 17.

[44] Vishay, Wet Electrolyte Tantalum Capacitors, Introduction

[45] Self-healing Characteristics of Solid Electrolytic Capacitor with Polypyrrole Electrolyte, Yamamoto Hideo

[46] Tettex instruments, SF_6 Gas insulated Standard Capacitors

[47] AVX, Performance Characteristics of Multilayer Glass Capacitors

[48] Murata: Basics of capacitors, lesson 2 Includes graph showing impedance as a function of frequency for different capacitor types; electrolytics are the only ones with a large component due to ESR

[49] Siliziumkondensator, Vishay, HPC0603A

[50] Simic Electronics, Chip Mica Capacitors

[51] AVX, NP0, 1000 pF 100 V, 0805, Q >= 1000 (1 MHz)

[52] WIMA, Selection of Capacitors for Pulse Applications

[53] Kemet, General information DC Film Capacitors

[54] Wima,Insulation Resistance

[55] Capacitors for reduced sound emissions

[56] Are your military ceramic capacitors subject to the piezoelectric effect?

[57] Kemet, Polymer Tantalum Chip Capacitors

[58] AVX, ANALYSIS OF SOLID TANTALUM CAPACITOR LEAKAGE CURRENT

[59] "Understand Capacitor Soakage to Optimize Analog Systems" by Bob Pease 1982

[60]
- "Modeling Dielectric Absorption in Capacitors", by Ken Kundert

[61] NCC, KME series

[62] KEMET, series PHE450

[63] Ralph M. Kerrigan, NWL Capacitor Division Metallized Polypropylene Film Energy Storage Capacitors For Low Pulse Duty

[64] / docs/datasheet_hc_series_1013793.pdf Maxwell HC Series

[65] K. W. Plessner (1956), "Ageing of the Dielectric Properties of Barium Titanate Ceramics" (in German), *Proceedings of the Physical Society. Section B* **69**: pp. 1261–1268, doi:10.1088/0370-1301/69/12/309

[66] Takaaki Tsurumi & Motohiro Shono & Hirofumi Kakemoto & Satoshi Wada & Kenji Saito & Hirokazu Chazono, Mechanism of capacitance aging under DC-bias field in X7R-MLCCs Published online: 23 March 2007, # Springer Science + Business Media, LLC 2007

[67] Christopher England, Johanson dielectrics, Ceramic Capacitor Aging Made Simple

[68] Dr. Arne Albertsen, Jianghai Europe, Electrolytic Capacitor Lifetime Estimation

[69] IEC/EN 61709, Electric components. Reliability. Reference conditions for failure rates and stress models for conversion

[70] MIL-HDBK-217F Reliability Prediction of Electronic Equipment

[71] J. L. Stevens, T. R. Marshall, A. C. Geiculescu M., C. R. Feger, T. F. Strange, Carts USA 2006, The Effects of Electrolyte Composition on the Deformation Characteristics of Wet Aluminum ICD Capacitors

[72] Alfonso Berduque, Zongli Dou, Rong Xu, BHC Components Ltd (KEMET), pdf Electrochemical Studies for Aluminium Electrolytic Capacitor Applications: Corrosion Analysis of Aluminium in Ethylene Glycol-Based Electrolytes

[73] Vishay BCcomponents, Revision: 10-May-12, Document Number: 28356, Introduction Aluminum Capacitors, paragraph "Storage"

[74] IEC/EN/DIN Standards, Beuth-Verlag

[75] highbeam business, Electronic Capacitors SIC 3675, Industry report

2.9 External links

- Spark Museum (von Kleist and Musschenbroek)
- Modeling Dielectric Absorption in Capacitors
- A different view of all this capacitor stuff
- Images of different types of capacitors
- Overview of different capacitor types
- Capsite 2015 Introduction to capacitors

Chapter 3

Farad

Not to be confused with faraday (unit). For the former settlement in California, see Farad, California.

The **farad** (symbol: F) is the SI derived unit of electrical capacitance, the ability of a body to store an electrical charge. It is named after the English physicist Michael Faraday.

3.1 Definition

One farad is defined as the capacitance of a capacitor across which, when charged with one coulomb of electricity, there is a potential difference of one volt.[1] Conversely, it is the capacitance which, when charged to a potential difference of one volt, carries a charge of one coulomb.[2] A coulomb is equal to the amount of charge (electrons) produced by a current of one ampere (A) flowing for one second. For example, the voltage across the two terminals of a 2 F capacitor will increase linearly by 1 V when a current of 2 A flows through it for 1 second.

For most applications, the farad is an impractically large unit of capacitance. Most electrical and electronic applications are covered by the following SI prefixes:

- 1 mF (millifarad, one thousandth (10^{-3}) of a farad) = 1000 μF = 1000000 nF
- 1 μF (microfarad, one millionth (10^{-6}) of a farad) = 1000 nF = 1000000 pF
- 1 nF (nanofarad, one billionth (10^{-9}) of a farad) = 1000 pF
- 1 pF (picofarad, one trillionth (10^{-12}) of a farad)

3.1.1 Equalities

A farad has the base SI representation of: $s^4 \times A^2 \times m^{-2} \times kg^{-1}$

It can further be expressed as:

$$F = \frac{A \cdot s}{V} = \frac{J}{V^2} = \frac{W \cdot s}{V^2} = \frac{C}{V} = \frac{C^2}{J} = \frac{C^2}{N \cdot m} = \frac{s^2 \cdot C^2}{m^2 \cdot kg} = \frac{s^4 \cdot A^2}{m^2 \cdot kg} =$$

where A=ampere, V=volt, C=coulomb, J=joule, m=metre, N=newton, s=second, W=watt, kg=kilogram, Ω=ohm, H=henry.

3.2 History

The term “farad” was coined by Josiah Latimer Clark in 1861, in honor of Michael Faraday, but it was for a unit of quantity of charge.

3.3 Explanation

Examples of different types of capacitors

A capacitor consists of two conducting surfaces, frequently referred to as plates, separated by an insulating layer usually referred to as a dielectric. The original capacitor was the Leyden jar developed in the 18th century. It is the accumulation of electric charge on the plates that results in capacitance. Modern capacitors are constructed using a range of manufacturing techniques and materials to provide the extraordinarily wide range of capacitance values used in electronics applications from femtofarads to farads, with maximum-voltage ratings ranging from a few volts to several kilovolts.

Values of capacitors are usually specified in **farads** (F), **microfarads** (μF), **nanofarads** (nF) and **picofarads** (pF).[3] The millifarad is rarely used in practice (a capacitance of 4.7 mF (0.0047 F), for example, is instead written as 4700 µF), while the nanofarad is uncommon in North America.[4] The size of commercially available capacitors ranges from around 0.1 pF to 5000F (5 kF) supercapacitors. Parasitic capacitance in high-performance integrated circuits can be measured in femtofarads (1 fF = 0.001 pF = 10^{-15} F), while high-performance test equipment can detect changes in capacitance on the order of tens of attofarads (1 aF = 0.000001 pF = 10^{-18} F).[5]

A value of 0.1 pF is about the smallest available in capacitors for general use in electronic design, since smaller ones would be dominated by the parasitic capacitances of other components, wiring or printed circuit boards. Capacitance values of 1 pF or lower can be achieved by twisting two short lengths of insulated wire together.[6][7]

The capacitance of the Earth's ionosphere with respect to the ground is calculated to be about 1 F.[8]

3.3.1 Informal terminology

The picofarad is sometimes colloquially pronounced as “puff” or “pic”, as in “a ten-puff capacitor”.[9] Similarly, “mic” (pronounced “mike”) is sometimes used informally to signify microfarads. If the Greek letter µ is not available, the notation “uF” is often used as a substitute for "µF” in electronics literature. A “micro-microfarad” (µµF, and confusingly often mmf or MMF), an obsolete unit sometimes found in older texts, is the equivalent of a picofarad.[10]

3.3.2 Related concepts

The reciprocal of capacitance is called electrical elastance, the (non-standard, non-SI) unit of which is the daraf.[11]

3.4 CGS units

The **abfarad** (abbreviated abF) is an obsolete CGS unit of capacitance equal to 10^9 farads (1 gigafarad, GF). This very large unit is used in medical terminology only.

The **statfarad** (abbreviated statF) is a rarely used CGS unit equivalent to the capacitance of a capacitor with a charge of 1 statcoulomb across a potential difference of 1 statvolt. It is $1/(10^{-5}c^2)$ farad, approximately 1.1126 picofarads.

3.5 See also

- Supercapacitor

3.6 Notes

[1] *The International System of Units (SI)* (8th ed.). Bureau International des Poids et Mesures (International Committee for Weights and Measures). 2006. p. 144.

[2] Peter M B Walker, ed. (1995). *Dictionary of Science and Technology*. Larousse. ISBN 0752300105.

[3] Braga, Newton C. (2002). *Robotics, Mechatronics, and Artificial Intelligence*. Newnes. p. 21. ISBN 0-7506-7389-3. Retrieved 2008-09-17. Common measurement units are the microfarad (µF), representing 0.000,001 F; the nanofarad (nF), representing 0.000,000,001 F; and the picofarad (pF), representing 0.000,000,000,001 F.

[4] Platt, Charles (2009). *Make: Electronics: Learning Through Discovery*. O'Reilly Media. p. 61. ISBN 9781449388799. Retrieved 2014-07-22. Nanofarads are also used, more often in Europe than in the United States.

[5] Gregorian, Roubik (1976). *Analog MOS Integrated Circuits for Signal Processing*. John Wiley & Sons. p. 78.

[6] Pease, Bob (2 September 1993). “What's All This Femtoampere Stuff, Anyhow?". Electronic Design. Retrieved 2013-03-09.

[7] Pease, Bob (1 December 2006). “What's All This Best Stuff, Anyhow?". Electronic Design. Retrieved 2013-03-09.

[8] Williams, L. L. (January 1999). “Electrical Properties of the Fair-Weather Atmosphere and the Possibility of Observable Discharge on Moving Objects”. Retrieved 2012-08-13.

[9] “Puff”. Wolfram Research. Retrieved 2009-06-09.

[10] In texts prior to 1960, **mf** rather than the modern **µF** frequently represented microfarads. Similarly, **mmf** represented picofarads.

[11] “Daraf”. Webster's Online Dictionary. Retrieved 2009-06-19.

3.7 External links

- Farad unit conversion tool

3.8 Text and image sources, contributors, and licenses

3.8.1 Text

- **Capacitor** *Source:* http://en.wikipedia.org/wiki/Capacitor?oldid=650088139 *Contributors:* AxelBoldt, Sodium, Bryan Derksen, Zundark, Ap, Andre Engels, Fredbauder, Aldie, PierreAbbat, Ray Van De Walker, Merphant, Waveguy, Heron, Patrick, Tim Starling, Chan siuman, Modster, Dominus, Tjfulopp, Lousyd, Kku, Ixfd64, Ahoerstemeier, Mac, Stevenj, Muriel Gottrop, Theresa knott, Darkwind, Glenn, Bogdangiusca, Nikai, BAxelrod, Smack, Schneelocke, HolIgor, Timwi, Bemoeial, Wikiborg, Reddi, Denni, Sertrel, Maximus Rex, Furrykef, Populus, Omegatron, Phoebe, Thue, Francs2000, Phil Boswell, Rogper, Nufy8, Robbot, Hubertus, Naddy, Modulatum, Texture, Gidonb, Jondel, Intangir, Jleedev, Rik G., Wjbeaty, Giftlite, DavidCary, Wolfkeeper, Netoholic, Tom harrison, Tubular, Everyking, CyborgTosser, Niteowlneils, Leonard G., Starsong, Guanaco, Yekrats, Mboverload, Pascal666, Solipsist, Foobar, Edcolins, StuartH, SebastianBreier, Geni, Gzuckier, Mako098765, MisfitToys, Am088, ShakataGaNai, Jossi, Hutschi, Anythingyouwant, Icairns, Gscshoyru, Urhixidur, Shen, Joyous!, Sonett72, Deglr6328, Xspartachris, Grunt, Gazpacho, Fpga, Ralph Corderoy, NathanHurst, Discospinster, Guanabot, ArnoldReinhold, Flatline, ZeroOne, Kjoonlee, FrankCostanza, Rmcii, Sietse Snel, RoyBoy, Euyyn, Mickeymousechen, Jevinsweval, Sole Soul, Bobo192, Shenme, Slicky, Bert Hickman, Kjkolb, Tgabor, Hagerman, Pearle, Hooperbloob, Jakew, Jumbuck, Neonumbers, Atlant, Mac Davis, Wdfarmer, Snowolf, Velella, CaseInPoint, Wtshymanski, Suruena, TenOfAllTrades, LFaraone, DV8 2XL, Gene Nygaard, Alai, Mattbrundage, HenryLi, Kenyon, Saeed, Robin F., Woohookitty, Poppafuze, Mindmatrix, RHaworth, StradivariusTV, Robert K S, Pol098, Tylerni7, Rtdrury, Gyanprakash, SCEhardt, Eyreland, SDC, Frankie1969, Wayward, Pfalstad, Msiddalingaiah, Graham87, Crocodealer, FreplySpang, Snafflekid, Edison, Josh Parris, Sjakkalle, Rjwilmsi, Zbxgscqf, Tangotango, Tawker, Vegaswikian, SeanMack, FlavrSavr, Thedatastream, FlaBot, Bobstay, Arnero, Shultzc, Jak123, Nivix, Alfred Centauri, Alex Sims, RexNL, Gurch, Czar, Pewahl, Fosnez, Fresheneesz, Fct, Chobot, Krishnavedala, DVdm, YurikBot, Wavelength, Jimp, Adam1213, RussBot, Gokselgoksel, Crazytales, Red Slash, Hydrargyrum, Akamad, Stephenb, Yyy, Shaddack, Wiki alf, Spike Wilbury, Howcheng, Sangwine, CecilWard, Mikeblas, RUL3R, E2mb0t, Zzzzzzus, Ospalh, Syrthiss, Scottfisher, DeadEyeArrow, Bota47, Supspirit, Dingy, Zelikazi, Smaines, Kev Boy, Wknight94, SamuelRiv, Searchme, Light current, Huangcjz, Knotnic, Tabby, Canley, Fergofrog, LeonardoRob0t, Naught101, JLaTondre, Enkauston, GrinBot, Dkasak, Mejor Los Indios, Lunch, Sbyrnes321, Veinor, SmackBot, Amcbride, FunnyYetTasty, Steve carlson, Tarret, Pgk, Thorseth, Freestyle, Blue520, BMunage, Jbleecker, Eskimbot, Pedrose, Edgar181, Genisock, Relaxing, Gilliam, Skizzik, RHCD, Lindosland, Quinsareth, Persian Poet Gal, Oli Filth, Pylori, OrangeDog, Papa November, Epastore, Terraguy, Dual Freq, A. B., Langbein Rise, Bread2u, Theneokid, Rheostatik, MKB, Can't sleep, clown will eat me, Милан Јелисавчић, JonHarder, Addshore, SundarBot, Mugaliens, Cyhatch, Fuhghettaboutit, Radagast83, S Roper, Dreadstar, M jurrens, Minipie8, DMacks, Kotjze, Sadi Carnot, Kukini, Fjjf, DJIndica, Nmnogueira, SashatoBot, Harryboyles, Dbtfz, John, Jidanni, Zaphraud, FrozenMan, Notmicro, JorisvS, Ckatz, CyrilB, A. Parrot, Dicklyon, Optakeover, Dalstadt, Nwwaew, ShakingSpirit, Hgrobe, Hu12, Blackcloak, W0lfie, IanOfNorwich, Tawkerbot2, Chetvorno, Atomobot, Powerslide, GeordieMcBain, Nutster, CmdrObot, Irwangatot, Scohoust, MorkaisChosen, Ilikefood, Prlsmith, JohnCD, Nczempin, Orderinchaos, Jamoche, Zyxoas, WeggeBot, Seven of Nine, Mike5193, RP98007, Cydebot, Lemurdude, Zginder, JustinForce, My Flatley, DumbBOT, Electric squall, Fyedernoggersnodden, Thijs!bot, Wikid77, Drpixie, Ishdarian, Young Pioneer, Electron9, Leon7, FourBlades, Nick Number, Jauricchio, AntiVandalBot, Linksmask1, Opelio, Shirt58, Gef756, Indrek, BinaryFrog, DarthShrine, Lfstevens, Myanw, Andy.Cowley, Zondran, Geobio, Arch dude, Ron7684, Ccrrccrr, Andonic, Coolhandscot, PhilKnight, Meeples, Sangak, Magioladitis, VoABot II, Mondebleu, Xochimec, Nikevich, Catgut, Crunchy Numbers, User A1, Martynas Patasius, JaGa, Calltech, Oroso, S3000, Audi O Phile, Denis tarasov, Axlq, Rettetast, Bissinger, Fuzzyhair2, Avakar, Kateshortforbob, Freeboson, J.delanoy, Pharaoh of the Wizards, Nbauman, Uncle Dick, Jesant13, Monodb, Ganymedstanek, Lannocc1, McSly, Mbbradford, RiverBissonnette, Glens userspace watcher, Warut, Leodj1992, Szzuk, NewEnglandYankee, Vanished user 47736712, Potatoswatter, Ja 62, H1voltage, Alexander Bell, Mlewis000, Samkline, Idioma-bot, Funandtrvl, Deor, Ivor Catt, VolkovBot, Larryisgood, Orphic, Pleasantville, Pasquale.Carelli, Philip Trueman, TXiKiBoT, Circuit13, The Original Wildbear, BertSen, Lordvolton, Sankalpdravid, Qxz, Cloudswrest, Oxfordwang, Dendodge, Martin451, PaulTanenbaum, Inductiveload, Nelkins, Yk Yk Yk, Synthebot, Altermike, GlassFET, Michaeltripp, Spinningspark, Antosheryl, Nibios, BeowulfNode, Symane, S.Örvarr.S, Theoneintraining, SieBot, Hertz1888, VVVBot, Trigaranus, Mwaisberg, Bentogoa, A. Carty, Ioverka, PHermans, Hello71, KoshVorlon, Steven Zhang, Lightmouse, Alex.muller, Ngriffeth, Fullobeans, PlantTrees, Treekids, TreeSmiler, Asher196, Dp67, SpectrumAnalyser, ClueBot, Binksternet, GorillaWarfare, Snigbrook, Robchat, Wanderer57, GreenSpigot, Mild Bill Hiccup, Ventusa, Edlerk, Enghoff, Pointillist, Nima shoormeij, Excirial, Jusdafax, Robbie098, Anon lynx, Lucas the scot, Dagordon01, Tylerdmace, Iner22, Esbboston, Brews ohare, Simdude2u, Jotterbot, Promethean, Etcwebb, Editor510, Banime, Thingg, Wstorr, Tleave2000, Berean Hunter, Elcap, DumZiBoT, InternetMeme, AlanM1, XLinkBot, BodhisattvaBot, Rror, Cameracut, Dthomsen8, Noctibus, WikiDao, Airplaneman, Alex Khimich, Addbot, Mortense, Landon1980, KickimusButtus, Ronhjones, Jncraton, Pcormon, Cst17, MrOllie, Download, LaaknorBot, Redheylin, Favonian, K Eliza Coyne, LinkFA-Bot, Peti610botH, Himerish, Numbo3-bot, Corny131, StoneCold89, Tide rolls, Luckas-bot, Yobot, Zaereth, Schuym1, Kartano, Jordsan, Amirobot, Mmxx, THEN WHO WAS PHONE?, AnomieBOT, Sonia, Jim1138, Jeni, B137, GRDoss, Materialscientist, Citation bot, Hadaly, OllieFury, ArthurBot, Xqbot, Capricorn42, Jeffrey Mall, Yuiwii, Turk oğlan, ManasShaikh, Mmathiesen, Wingstarsoft, GrouchoBot, Mdewman6, RibotBOT, Epannila, Leonardo Da Vinci, Quantum ammar, Thaflinger, GhalyBot, Grossday, Chongkian, Dougofborg, Coleycole, GliderMaven, FrescoBot, Feneeth of Borg, RuslanBer, Yiyi303, Soam Vasani, Idyllic press, Hasanbabu, Craig Pemberton, Rjwiki09, Citation bot 1, Pinethicket, Jonesey95, Tom.Reding, RedBot, 124Nick, Foobarnix, Fumitol, Vin300, Abhishekchavan79, Hitachi-Train, LogAntiLog, Dinamik-bot, Vrenator, MajorStovall, TorQue Astur, Theo10011, Vladislav Pogorelov, Minimac, Rad peeps, Hyarmendacil, NerdyScienceDude, Cogniac, Bullet train, Mark Kretschmar, EmausBot, WikitanvirBot, Hippopenonomous, Da500063, GoingBatty, Minimac's Clone, DMChatterton, Tommy2010, Gavinburke, REMspectrum, Frof eyed, ZéroBot, Lindseyrose, Sanalks, Fred Gandt, L Kensington, Zueignung, Ego White Tray, DennisIsMe, Itaharesay, Maminov2, TYelliot, ClueBot NG, Ulflund, Matthiaspaul, Vividvilla, Delusion23, 10v1walsha, ScottSteiner, Benfriesen12, Widr, Reify-tech, Vortex112, Helpful Pixie Bot, Lowercase sigmabot, Mataresephotos, BG19bot, IronOak, Vagobot, Vokesk, AntonioSajonia, Piguy101, Mark Arsten, AhsanAli408, Rickey985, Isacp, Sleepsfortheweak, Frizb99, BattyBot, Clienthopeless, DarafshBot, Mahmud Halimi Wardag, HubabubbalubbahubbaYABALICIOUS, SD5bot, JamesHaigh, Kshahinian, Dexbot, Aloysius314, Mogism, Salako1999, Bayezit.dirim, Isarra (HG), MZLauren, Frosty, Paxmartian, FrostieFrost, Vahid alpha, Madhacker2000, Mark viking, Altered Walter, TREXJET, Fa.aref, Gomunkul51, Murmur75, Gtrsentra, DavidLeighEllis, Glaisher, Jwratner1, Asadwarraich, Cricetone, Monkbot, JREling1, JaunJimenez, MadDoktor23, Applemusher123, NameloCmaS, Krelcoyne, Ruksakba and Anonymous: 1026
- **Types of capacitor** *Source:* http://en.wikipedia.org/wiki/Types%20of%20capacitor?oldid=649535463 *Contributors:* Jengod, Omegatron, Centrx, DavidCary, Leonard G., Rchandra, Foobar, Vadmium, Chowbok, Klemen Kocjancic, Fuzlyssa, Adam850, LindsayH, Smalljim, Cmdrjameson, Courtarro, Giraffedata, Bert Hickman, Hooperbloob, Alansohn, Yossiea, Wtshymanski, DV8 2XL, Gene Nygaard, Mindmatrix, Pol098, Rtdrury, Eyreland, The Lightning Stalker, Edison, Rjwilmsi, Ctdunstan, Vegaswikian, Arnero, Ewlyahoocom, KFP, Tylerl, Krishnavedala, DVdm, Dbagnall, Hellbus, Shaddack, Anomalocaris, Friederich, Sangwine, Mikeblas, FF2010, Light current, Tabby, JLa-

Tondre, Groyolo, Cynthia Bennett, SmackBot, FunnyYetTasty, Hydrogen Iodide, Commander Keane bot, Unforgettableid, QEDquid, Chris the speller, AhmedHan, Papa November, Colonies Chris, Dual Freq, OrphanBot, E.boyer7, CyrilB, Stwalkerster, Condem, DabMachine, ERAGON, Mikiemike, Dkazdan, CmdrObot, Ilikefood, Branclem, Ozguy89, Parsa, Wikid77, Pjvpjv, DmitTrix, Nick Number, Malvineous, Indrek, Lfstevens, Xhienne, Chungalin, Arch dude, RastaKins, JamesBWatson, SwiftBot, R'n'B, Maproom, Kundert, Mbbradford, Warut, KylieTastic, Funandtrvl, Philip Trueman, Circuit13, The Original Wildbear, Jackfork, PouponOnToast, Dodger67, Asher196, Kinzele, Dp67, Jan1nad, Sun Creator, Arjayay, SchreiberBike, Elcap, AlanM1, WackyBoots, Addbot, Mortense, Fbfree, Vyom25, Wikipongdia, Tide rolls, Yobot, AnomieBOT, BlazerKnight, Materialscientist, LilHelpa, Eric Hegi, J04n, Chongkian, Shadowjams, RGForbes, FrescoBot, Worky worky, Sisyphustkd, Techauthor, Pinethicket, I dream of horses, Calmer Waters, KyleB68, Vladislav Pogorelov, Brteag00, Hosomaki, John of Reading, Pbfy0, Fred Gandt, Makecat, ClueBot NG, Shaddim, Tylko, Widr, Reify-tech, BG19bot, MusikAnimal, DPL bot, Khazar2, MadCowpoke, Cerabot, JAC4, Purpletin, Jodosma, Tsylonen, WPGA2345, JustinTG86 and Anonymous: 122

- **Farad** *Source:* http://en.wikipedia.org/wiki/Farad?oldid=647678569 *Contributors:* Marj Tiefert, Bryan Derksen, Christian List, Maury Markowitz, Heron, Leandrod, Collabi, Glenn, Rob Hooft, Schneelocke, Hashar, Andrewman327, Omegatron, Indefatigable, Secretlondon, Jerzy, Carlossuarez46, AlexPlank, Robbot, Bkell, Davidjonsson, Ancheta Wis, Giftlite, Karn, Brockert, Matthäus Wander, Bobblewik, Edcolins, Icairns, Urhixidur, CALR, Vincom2, Andros 1337, Eitheladar, ArnoldReinhold, Smyth, Jcmaco, Murtasa, Kms, Liberatus, Bdoserror, Jonah.ru, Femto, Rbj, Dungodung, Larry V, Orzetto, Stovetopcookies, Dirac1933, Gene Nygaard, Cbdorsett, Isnow, BD2412, NebY, Vegaswikian, Andrew Rodland, FlaBot, Acyso, Fresheneesz, Chobot, Turidoth, Theorbtwo, YurikBot, Angus Lepper, Spike Wilbury, Grafen, Brad Eleven, Bota47, Deeday-UK, HereToHelp, Shevonsilva, SmackBot, Chris the speller, Bluebot, Thumperward, Oli Filth, DHN-bot, MarkMentovai, Eliyak, FrozenMan, Bjankuloski06en, Siby1, Chovain, Syphondu, Ghsrocketman, Meno25, Zginder, Peter439, Wikid77, Headbomb, Escarbot, Pro crast in a tor, Indrek, JAnDbot, Harryzilber, Jqavins, Magioladitis, WhatamIdoing, Edurant, Leyo, Warut, Specter01010, Idioma-bot, VolkovBot, VasilievVV, Lingwitt, TXiKiBoT, Hqb, Erikev, Awl, BotKung, AlleborgoBot, SieBot, Hertz1888, WarrenPlatts, ScAvenger lv, ClueBot, Fujinvsjax, Ktr101, Excirial, Dannyn99, Gciriani, DumZiBoT, SuddenFrost, AlanM1, Bondrake, Thatguyflint, Tubesship, Addbot, Mortense, Jafeluv, AkhtaBot, TutterMouse, AndersBot, Numbo3-bot, Ehrenkater, Lightbot, Luckas-bot, Fraggle81, Amirobot, Materialscientist, GrouchoBot, Amaury, Nedim Ardoğa, FrescoBot, D'ohBot, Steve Quinn, InternetFoundation, Sneller2, TobeBot, 777sms, Cpy.Prefers.You, Tbhotch, Stroppolo, OydauKlop, EmausBot, Westley Turner, Joshlepaknpsa, Yerocus, LittleMorgenChe, Mikhail Ryazanov, ClueBot NG, Dylantv, Infinity Warrior, Matthiaspaul, ReecyBoy42, GKFX, Zyxwv99, HMman, Douglou, Oleh Svintsitskyy, ChrisGualtieri, Hmainsbot1, Togoforit, Offling, WertMooMoo, Oldhonger, Coreyemotela, Monkbot and Anonymous: 148

3.8.2 Images

- **File:Axial_electrolytic_capacitors.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/b/b4/Axial_electrolytic_capacitors.jpg *License:* CC BY 3.0 *Contributors:* http://matarese.com/photo/413-sprague-atom-electrolytics/ *Original artist:* Mataresephotos
- **File:Capacitor-Series-Equivalent-Circuit-.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/9/9d/Capacitor-Series-Equivalent-Circuit-.png *License:* CC0 *Contributors:* Own work *Original artist:* Elcap
- **File:Capacitor-symbol-bipolar-El-Cap.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/4/44/Capacitor-symbol-bipolar-El-Cap.png *License:* CC0 *Contributors:* Own work *Original artist:* Elcap
- **File:Capacitor.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/5/5a/Capacitor.jpg *License:* CC BY-SA 3.0 *Contributors:* Transferred from en.wikipedia; transferred to Commons by User:Sreejithk2000 using CommonsHelper.
Original artist: Daniel Christensen at en.wikipedia
- **File:CapacitorHydraulicAnalogyAnimation.gif** *Source:* http://upload.wikimedia.org/wikipedia/commons/c/c1/CapacitorHydraulicAnalogyAnimation.gif *License:* CC0 *Contributors:* Own work *Original artist:* Sbyrnes321
- **File:Capacitor_Miniaturizing_1970-2005.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/d/d2/Capacitor_Miniaturizing_1970-2005.png *License:* CC0 *Contributors:* Own work *Original artist:* Elcap
- **File:Capacitor_equivalent_circuits.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/a/a8/Capacitor_equivalent_circuits.svg *License:* CC0 *Contributors:* Own work *Original artist:* GorillaWarfare
- **File:Capacitor_schematic_with_dielectric.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/c/cd/Capacitor_schematic_with_dielectric.svg *License:* CC BY-SA 3.0 *Contributors:* self-made SVG version of Image:Dielectric.png, incorporating Image:Capacitor schematic.svg as its base. *Original artist:* Papa November
- **File:Capacitor_symbol.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/0/0a/Capacitor_symbol.png *License:* Public domain *Contributors:* ? *Original artist:* ?
- **File:Capacitors-AC_limiting_conditions.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/9/96/Capacitors-AC_limiting_conditions.png *License:* CC0 *Contributors:* Own work *Original artist:* Elcap
- **File:Capacitors-Overlapping-Applications.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/2/29/Capacitors-Overlapping-Applications.png *License:* CC0 *Contributors:* Own work *Original artist:* Elcap
- **File:Capacitors_(7189597135).jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/b/b9/Capacitors_%287189597135%29.jpg *License:* CC BY-SA 2.0 *Contributors:* 12739s *Original artist:* Eric Schrader from San Francisco, CA, United States
- **File:Capacitors_Various.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/c/c8/Capacitors_Various.jpg *License:* Public domain *Contributors:* Own work *Original artist:* Intiti.
- **File:Capacitors_in_parallel.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/f/fa/Capacitors_in_parallel.svg *License:* CC BY-SA 3.0 *Contributors:* This SVG electrical schematic was created with the Electrical Symbols Library. *Original artist:* Omegatron0
- **File:Capacitors_in_series.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/7/75/Capacitors_in_series.svg *License:* CC BY-SA 3.0 *Contributors:* This SVG electrical schematic was created with the Electrical Symbols Library. *Original artist:* Omegatron0
- **File:Commons-logo.svg** *Source:* http://upload.wikimedia.org/wikipedia/en/4/4a/Commons-logo.svg *License:* ? *Contributors:* ? *Original artist:* ?

- **File:Condensador_electrolitico_150_microF_400V.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/3/31/Condensador_electrolitico_150_microF_400V.jpg *License:* CC BY-SA 3.0 *Contributors:* Own work *Original artist:* Willtron
- **File:Condensators.JPG** *Source:* http://upload.wikimedia.org/wikipedia/commons/d/de/Condensators.JPG *License:* CC-BY-SA-3.0 *Contributors:* de:Bild:Kondensatoren.JPG, uploaded there by de:Benutzer:Honina *Original artist:* de:Benutzer:Aka
- **File:Condensor_bank_150kV_-_75MVAR.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/e/ed/Condensor_bank_150kV_-_75MVAR.jpg *License:* Public domain *Contributors:* Own work *Original artist:* Philippe Mertens
- **File:Delta-Cap-versus-Zeit-engl.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/b/be/Delta-Cap-versus-Zeit-engl.png *License:* CC0 *Contributors:* Own work *Original artist:* Elcap
- **File:E-cap-family-14-02-02.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/2/2e/E-cap-family-14-02-02.jpg *License:* CC0 *Contributors:* Own work *Original artist:* Elcap
- **File:EDLC-Classes.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/b/b4/EDLC-Classes.png *License:* CC0 *Contributors:* Own work *Original artist:* Elcap
- **File:Electric_double-layer_(BMD_model)_NT.PNG** *Source:* http://upload.wikimedia.org/wikipedia/commons/7/7e/Electric_double-layer_%28BMD_model%29_NT.PNG *License:* CC BY 3.0 *Contributors:* Own work *Original artist:* Tosaka
- **File:Electrolytic_capacitor.jpg** *Source:* http://upload.wikimedia.org/wikipedia/en/a/a6/Electrolytic_capacitor.jpg *License:* CC-BY-3.0 *Contributors:*

  photo

  Original artist:

  Vahid alpha
- **File:Elko-Badewannenkurve-english.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/5/5b/Elko-Badewannenkurve-english.png *License:* CC0 *Contributors:* Own work *Original artist:* Elcap
- **File:Feed_through_capacitor_symbol.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/3/32/Feed_through_capacitor_symbol.png *License:* CC0 *Contributors:* Own work *Original artist:* Elcap
- **File:Film-Cap-Pulse-Strength-Versions.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/a/a7/Film-Cap-Pulse-Strength-Versions.svg *License:* CC0 *Contributors:* Own work *Original artist:* Elcap
- **File:Fixed_capacitors-charge_storage_principles-2.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/a/a6/Fixed_capacitors-charge_storage_principles-2.png *License:* CC0 *Contributors:* Own work *Original artist:* Elcap
- **File:Fixed_capacitors_overview.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/0/05/Fixed_capacitors_overview.svg *License:* CC BY-SA 4.0 *Contributors:* Own work *Original artist:* Krishnavedala
- **File:Folder_Hexagonal_Icon.svg** *Source:* http://upload.wikimedia.org/wikipedia/en/4/48/Folder_Hexagonal_Icon.svg *License:* Cc-by-sa-3.0 *Contributors:* ? *Original artist:* ?
- **File:Folko-U-eff-f-Frequenz.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/e/eb/Folko-U-eff-f-Frequenz.png *License:* CC-BY-SA-3.0 *Contributors:* Own work *Original artist:* Elcap, Jens Both
- **File:Kondensator-Impedanzverläufe-Wiki-1.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/d/d4/Kondensator-Impedanzverl%C3%A4ufe-Wiki-1.jpg *License:* CC-BY-SA-3.0 *Contributors:* Own work *Original artist:* Elcap, Jens Both
- **File:Kondensator_Zeigerdiagramm-1-.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/3/33/Kondensator_Zeigerdiagramm-1-.svg *License:* CC-BY-SA-3.0 *Contributors:* Zeichnung von Saure von 2009-6-3 ergänzt mit „tan d“ *Original artist:* Saure, ergänzt durch Elcap, Jens Both
- **File:Kondensatoren-Kap-Versus-Spg-English.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/9/93/Kondensatoren-Kap-Versus-Spg-English.svg *License:* CC0 *Contributors:* Own work *Original artist:* Elcap
- **File:Leakage_current_curves.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/0/0f/Leakage_current_curves.png *License:* CC0 *Contributors:* Own work *Original artist:* Elcap
- **File:Lebensdauer-Testergebnisse-english.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/8/8b/Lebensdauer-Testergebnisse-english.png *License:* CC0 *Contributors:* Own work *Original artist:* Elcap
- **File:Leidse_flessen_Museum_Boerhave_december_2003_2.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/2/22/Leidse_flessen_Museum_Boerhave_december_2003_2.jpg *License:* CC-BY-SA-3.0 *Contributors:* Originally from en.wikipedia; description page is/was here.
  Original Image: en::Image:Leidse flessen Museum Boerhave december 2003.jpg *Original artist:* Original uploader was Alvinrune at en.wikipedia
- **File:MKV-Power-Capacitor-Construction.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/6/62/MKV-Power-Capacitor-Construction.svg *License:* CC0 *Contributors:* Own work *Original artist:* Elcap
- **File:MLCC-Construction.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/c/ce/MLCC-Construction.png *License:* CC0 *Contributors:* Own work *Original artist:* Elcap
- **File:Mylar-film_oil-filled_low-inductance_capacitor_6.5_MFD_@_5000_VDC.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/2/2d/Mylar-film_oil-filled_low-inductance_capacitor_6.5_MFD_%40_5000_VDC.jpg *License:* CC0 *Contributors:* Own work *Original artist:* Zaereth
- **File:Nuvola_apps_ksim.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/8/8d/Nuvola_apps_ksim.png *License:* LGPL *Contributors:* http://icon-king.com *Original artist:* David Vignoni / ICON KING
- **File:OneFarad5.5Velectrolyticcapacitor.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/1/1d/OneFarad5.5Velectrolyticcapacitor.jpg *License:* Public domain *Contributors:* Own work *Original artist:* Xpixupload
- **File:OscillatorSchematic.png** *Source:* http://upload.wikimedia.org/wikipedia/en/2/2b/OscillatorSchematic.png *License:* CC-BY-3.0 *Contributors:* ? *Original artist:* ?

- **File:Parallel_plate_capacitor.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/3/35/Parallel_plate_capacitor.svg *License:* Public domain *Contributors:* own drawing, done in Inkscape 0.44 *Original artist:* inductiveload
- **File:Photo-SMDcapacitors.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/8/86/Photo-SMDcapacitors.jpg *License:* Public domain *Contributors:* ? *Original artist:* ?
- **File:Plattenkondensator_hg.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/d/d3/Plattenkondensator_hg.jpg *License:* CC BY 3.0 *Contributors:* own work, Schulhistorische Sammlung Bremerhaven *Original artist:* Hannes Grobe (talk)
- **File:Polarized_capacitor_symbol.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/f/f2/Polarized_capacitor_symbol.png *License:* CC BY-SA 3.0 *Contributors:* ? *Original artist:* ?
- **File:Polarized_capacitor_symbol_2.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/5/51/Polarized_capacitor_symbol_2.png *License:* Public domain *Contributors:* ? *Original artist:* ?
- **File:Polarized_capacitor_symbol_3.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/3/39/Polarized_capacitor_symbol_3.png *License:* CC BY-SA 3.0 *Contributors:* ? *Original artist:* ?
- **File:Polyester_film_capacitor.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/1/13/Polyester_film_capacitor.jpg *License:* CC BY 3.0 *Contributors:* http://matarese.com/photo/418-mallory-150-capacitor/ *Original artist:* Mataresephotos
- **File:Power_vs_energy_density_3.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/e/e0/Power_vs_energy_density_3.svg *License:* CC BY-SA 3.0 *Contributors:* Own work *Original artist:* Shaddim
- **File:Question_book-new.svg** *Source:* http://upload.wikimedia.org/wikipedia/en/9/99/Question_book-new.svg *License:* Cc-by-sa-3.0 *Contributors:*

  Created from scratch in Adobe Illustrator. Based on Image:Question book.png created by User:Equazcion *Original artist:*
  Tkgd2007
- **File:RC_switch.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/9/90/RC_switch.svg *License:* CC BY-SA 3.0 *Contributors:* Own work *Original artist:* PureCore
- **File:Rated-Category.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/6/60/Rated-Category.png *License:* CC0 *Contributors:* Own work *Original artist:* Elcap
- **File:SI_base_unit.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/c/c8/SI_base_unit.svg *License:* CC BY-SA 3.0 *Contributors:* I (Dono (talk)) created this work entirely by myself. Base on http://www.newscientist.com/data/images/archive/2622/26221501.jpg *Original artist:* Dono (talk)
- **File:Supercapacitors-Short-Overview.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/2/24/Supercapacitors-Short-Overview.png *License:* CC0 *Contributors:* Own work *Original artist:* Elcap
- **File:Symbol_book_class2.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/8/89/Symbol_book_class2.svg *License:* CC BY-SA 2.5 *Contributors:* Mad by Lokal_Profil by combining: *Original artist:* Lokal_Profil
- **File:Tantalum_capacitors.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/e/e0/Tantalum_capacitors.jpg *License:* CC BY 3.0 *Contributors:* http://matarese.com/photo/419-several-tantalum-capacitors/ *Original artist:* Mataresephotos
- **File:Trimmer-capacitor-symbol.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/4/43/Trimmer-capacitor-symbol.png *License:* CC0 *Contributors:* Own work *Original artist:* Elcap
- **File:Types_of_capacitor.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/1/1c/Types_of_capacitor.svg *License:* CC0 *Contributors:* Vectorized from raster image at English Wikipedia. *Original artist:* Uploader is Jwratner1 at English Wikipedia.
- **File:Variable_capacitor_symbol.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/b/b2/Variable_capacitor_symbol.png *License:* Public domain *Contributors:* Own work *Original artist:* Uploaded by Wikimedia Commonplace
- **File:Verschiedene_Kondensatoren_2.JPG** *Source:* http://upload.wikimedia.org/wikipedia/commons/9/92/Verschiedene_Kondensatoren_2.JPG *License:* CC-BY-SA-3.0 *Contributors:* Transferred from de.wikipedia to Commons by User:Wdwd using CommonsHelper. *Original artist:* Fabian ~ (Fabian R at de.wikipedia)
- **File:Wikibooks-logo-en-noslogan.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/d/df/Wikibooks-logo-en-noslogan.svg *License:* CC BY-SA 3.0 *Contributors:* Own work *Original artist:* User:Bastique, User:Ramac et al.
- **File:Wiktionary-logo-en.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/f/f8/Wiktionary-logo-en.svg *License:* Public domain *Contributors:* Vector version of Image:Wiktionary-logo-en.png. *Original artist:* Vectorized by Fvasconcellos (talk · contribs), based on original logo tossed together by Brion Vibber

3.8.3 Content license

- Creative Commons Attribution-Share Alike 3.0