# CAPACITORS

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A **capacitor** or **condenser** is a passive electronic component consisting of a pair of conductors separated by a dielectric. When a voltage potential difference exists between the conductors, an electric field is present in the dielectric. This field stores energy and produces a mechanical force between the plates. The effect is greatest between wide, flat, parallel, narrowly separated conductors.

An ideal capacitor is characterized by a single constant value, capacitance, which is measured in farads. This is the ratio of the electric charge on each conductor to the potential difference between them. In practice, the dielectric between the plates passes a small amount of leakage current. The conductors and leads introduce an equivalent series resistance and the dielectric has an electric field strength limit resulting in a breakdown voltage.

## History

In October 1745, Ewald Georg von Kleist of Pomerania in 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. 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 after removing the generator, touching the wire resulted in a painful spark. In a letter describing the experiment, he said "I would not take a second shock for the kingdom of France." The following year, the Dutch physicist Pieter van Musschenbroek invented a similar capacitor, which was named the Leyden jar, after the University of Leyden where he worked. 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 proved that the charge was stored on the glass, not in the water as others had assumed. He also created the term "battery", (as in battery of cannon), subsequently applied to clusters of electrochemical cells. Leyden jars were later to be 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 nanofarad.

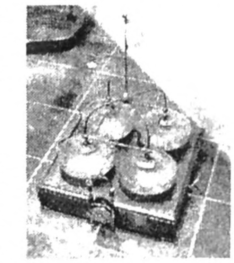
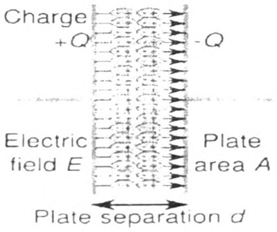


Fig.1 First generation Capacitor

## Theory of operation



A capacitor consists of two conductors separated by a non-conductive region. The non-conductive substance is called the dielectric medium, although this may also mean a vacuum or 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 an external electric field. The conductors thus contain equal and opposite charges on their facing surfaces, and the dielectric contains an electric field. The capacitor is a reasonably general model for electric fields within electric circuits.

Fig.2 Schematic diagram of a parallel plate capacitor

An ideal capacitor is wholly characterized by a constant capacitance '**C**', defined as the ratio of charge ±'**Q**' on each conductor to the voltage '**V**' between them

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

Sometimes charge buildup affects the mechanics of the capacitor, causing the capacitance to vary. In this case, capacitance is defined in terms of incremental changes:

$$C = \frac{\mathrm{d}q}{\mathrm{d}v}$$

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.

## Energy storage

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 and energy is stored in the electric field. If charge is later allowed to return to its equilibrium position, the energy is released. The work done in establishing the electric field, and hence the amount of energy stored, is given by:

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

## Current-voltage relation

The current i (t ) through a component in an electric circuit is defined as the rate of change of the charge q (t ) that has passed through it. Physical charges cannot pass through the dielectric layer of a capacitor, but rather build up in equal and opposite quantities on the electrodes: as each electron accumulates on the negative plate, one leaves the positive plate. Thus the accumulated charge on the electrodes is equal to the integral of the current, as well as being proportional to the voltage (as discussed above). As with any anti derivative, a constant of integration is added to represent the initial voltage v $(t_0)$. This is the integral form of the capacitor equation,

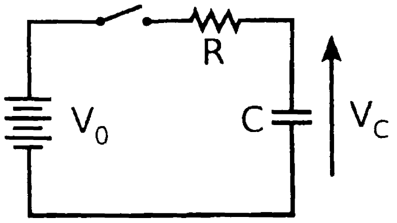
$$v(t) = \frac{q(t)}{C} = \frac{1}{C}\int_{t_0}^{t} i(\tau)\mathrm{d}\tau + v(t_0)$$

Taking the derivative of this, and multiplying by C, yields the derivative form

$$i(t) = \frac{\mathrm{d}q(t)}{\mathrm{d}t} = C\frac{\mathrm{d}v(t)}{\mathrm{d}t}.$$

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

**C circuits**



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.[10] 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

$$V_0 = v_{\text{resistor}}(t) + v_{\text{capacitor}}(t) = i(t)R + \frac{1}{C}\int_0^t i(\tau)\mathrm{d}\tau.$$

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, the differential equation yields

$$i(t) = \frac{V_0}{R} e^{-t/\tau_0} \qquad v(t) = V_0\left(1 - e^{-t/\tau_0}\right),$$

Where $\tau_0$ = RC is the time constant of the system.

As the capacitor reaches equilibrium with the source voltage, the voltage across the resistor and the current through the entire circuit decay. 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.

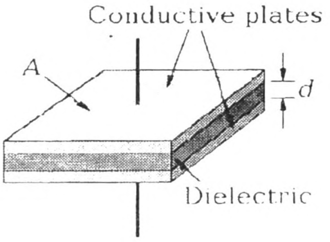
AC circuits

Impedance, the vector sum of reactance and resistance, describes the phase difference and the ratio of amplitudes between sinusoidal varying voltage and sinusoidal 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

Where j is the imaginary unit and ω is the angular velocity of the sinusoidal signal. The - j phase indicates that the AC voltage V = Z I 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.

## Parallel plate model

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



The simplest capacitor consists of two parallel conductive plates separated by a dielectric 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 ± ρ = ± 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 = ρ/ε. The voltage is defined as the line integral of the electric field between the plates

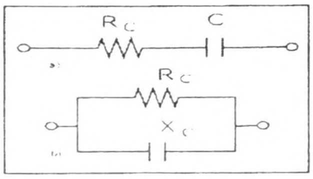
$$V = \int_0^d E\,\mathrm{d}z = \int_0^d \frac{\rho}{\varepsilon}\mathrm{d}z = \frac{\rho d}{\varepsilon} = \frac{Qd}{\varepsilon A}.$$

Solving this for C = Q/V reveals that capacitance increases with area and decreases with separation

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

The capacitance is therefore greatest in devices made from materials with a high permittivity.

## **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:

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

As frequency approaches infinity, the capacitive impedance (or reactance) approaches zero and the ESR becomes significant. As the reactance becomes negligible, power dissipation approaches $P_{RMS} = V_{RMS}^2 / R_{ESR}$.

## 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. Certain types of capacitors, such as electrolytic tantalum capacitors, usually have a rating for maximum ripple current (both in frequency and magnitude). This ripple current can cause damaging heat to be generated within the capacitor due to the current flow across resistive imperfections in the materials used within the capacitor, more commonly referred to as equivalent series resistance (ESR). For example electrolytic tantalum capacitors are limited by ripple current and generally have the highest ESR ratings in the capacitor family, while ceramic capacitors generally have no ripple current limitation and have some of the lowest ESR ratings.

## Applications

### System Energy Storage

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

(i) In car audio systems, large capacitors store energy for the amplifier to use on demand.

(ii) UPSes can be equipped with maintenance-free capacitors to extend service life.

### Power conditioning

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

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.

## References

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3). Ulaby, Fawwaz T. Fundamantals of Applied electromagnetism (1999 ed.), Prentice Hall.