Handbook of

Capacitors

(Electrical Components)

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First Edition, 2012

ISBN 978-81-323-1545-2

Published by:
Learning Press
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Ansari Road, Darya Ganj,
Delhi - 110002
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Capacitor

Modern capacitors, by a cm rule

A typical electrolytic capacitor

A **capacitor** (formerly known as **condenser**) is a passive electronic component consisting of a pair of conductors separated by a dielectric (insulator). When there is a potential difference (voltage) across the conductors, a static electric field develops in the dielectric that stores energy and produces a mechanical force between the conductors. An ideal capacitor is characterized by a single constant value, capacitance, measured in farads. This is the ratio of the electric charge on each conductor to the potential difference between them.

Capacitors are widely used in electronic circuits for blocking direct current while allowing alternating current to pass, in filter networks, for smoothing the output of power supplies, in the resonant circuits that tune radios to particular frequencies and for many other purposes.

The effect is greatest when there is a narrow separation between large areas of conductor, hence capacitor conductors are often called "plates", referring to an early means of construction. In practice the dielectric between the plates passes a small amount of leakage current and also has an electric field strength limit, resulting in a breakdown voltage, while the conductors and leads introduce an undesired inductance and resistance.

History

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

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, after removing the generator, that 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 Leiden where he worked.

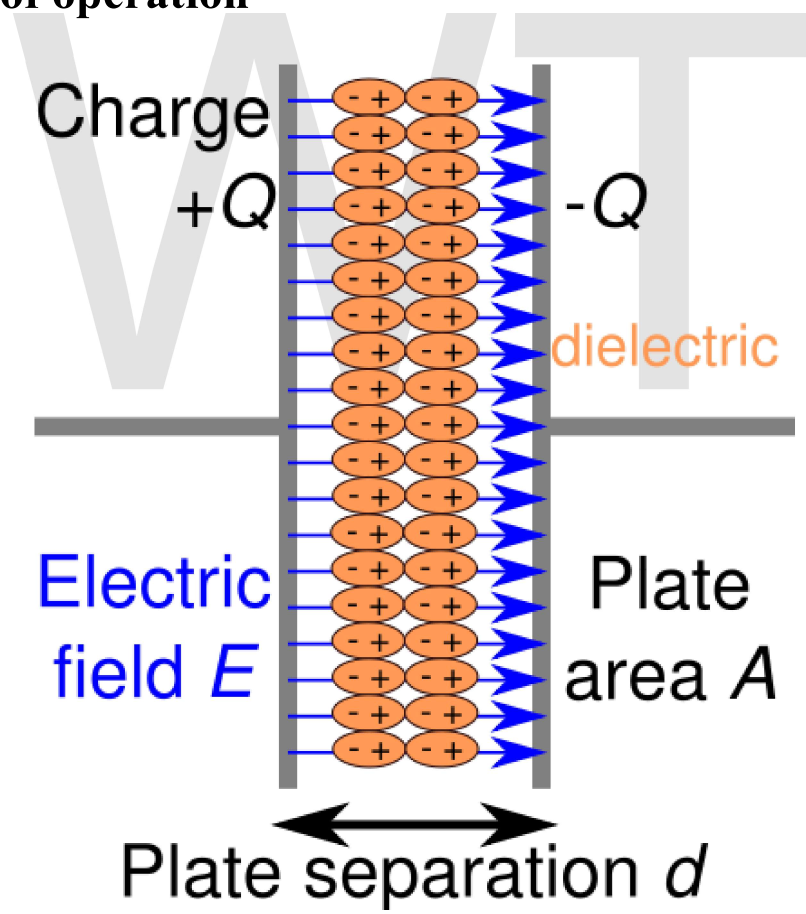
Daniel Gralath was the first to combine several jars in parallel into a "battery" to increase the charge storage capacity. Benjamin Franklin investigated the Leyden jar and "proved" that the charge was stored on the glass, not in the water as others had assumed. He also adopted the term "battery", (denoting the increasing of power with a row of similar units as in a battery of cannon), subsequently applied to clusters of electrochemical cells.

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 nanofarad.

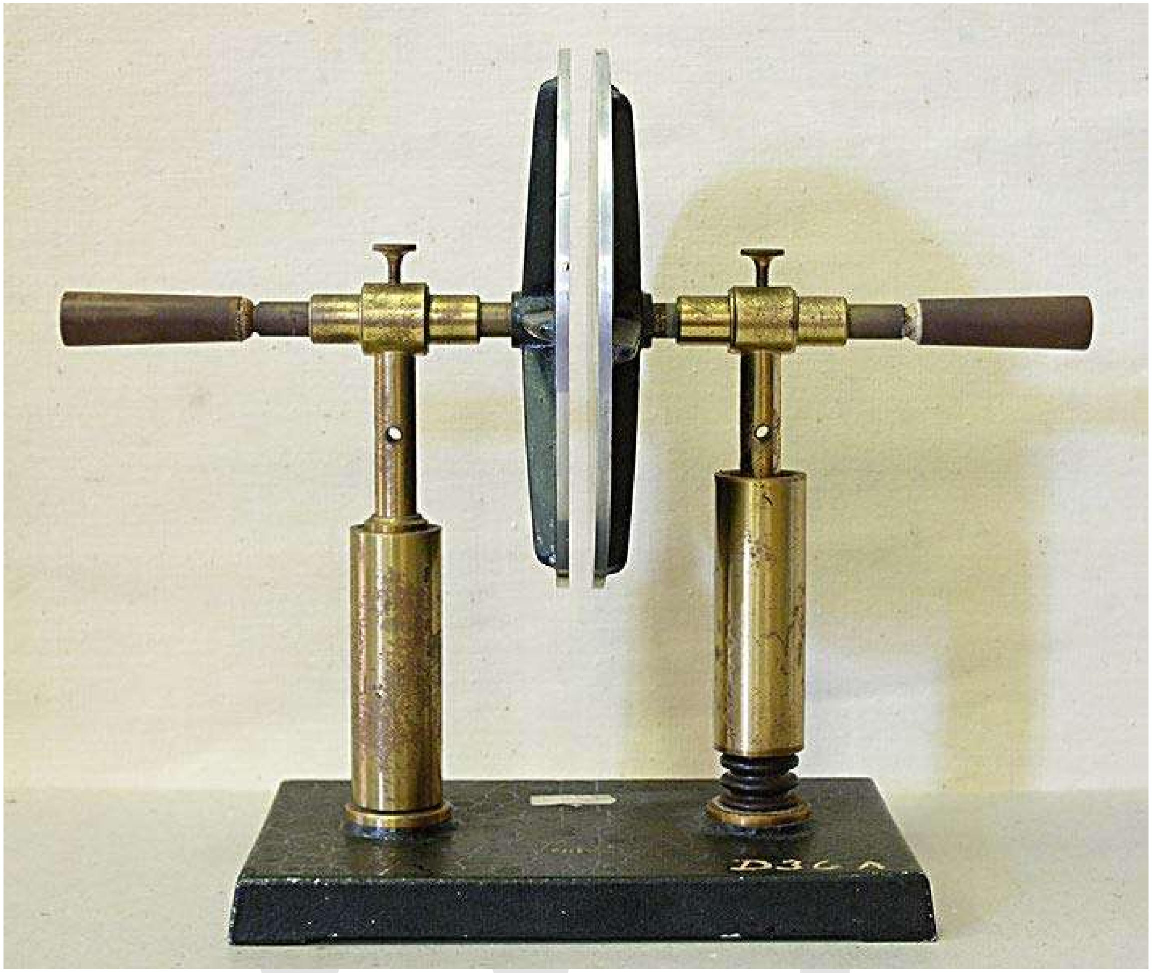
Leyden jars or more powerful devices employing flat glass plates alternating with foil conductors were used exclusively up until about 1900, when the invention of wireless (radio) created a demand for standard capacitors, and the steady move to higher frequencies required capacitors with lower inductance. A more compact construction began to be used of a flexible dielectric sheet such as 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. 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.

Theory of operation



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

A capacitor consists of two conductors separated by a non-conductive region called the dielectric medium though it may be 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 any external electric field. The conductors thus hold equal and opposite charges on their facing surfaces, 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.

The capacitor is a reasonably general model for electric fields within electric circuits. 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:

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

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

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

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 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 given by:

$$W = \int_{q=0}^{Q} V \mathrm{d}q = \int_{q=0}^{Q} \frac{q}{C} \mathrm{d}q = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}CV^2 = \frac{1}{2}VQ.$$

Current-voltage relation

The current $i(t)$ through 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 an 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,

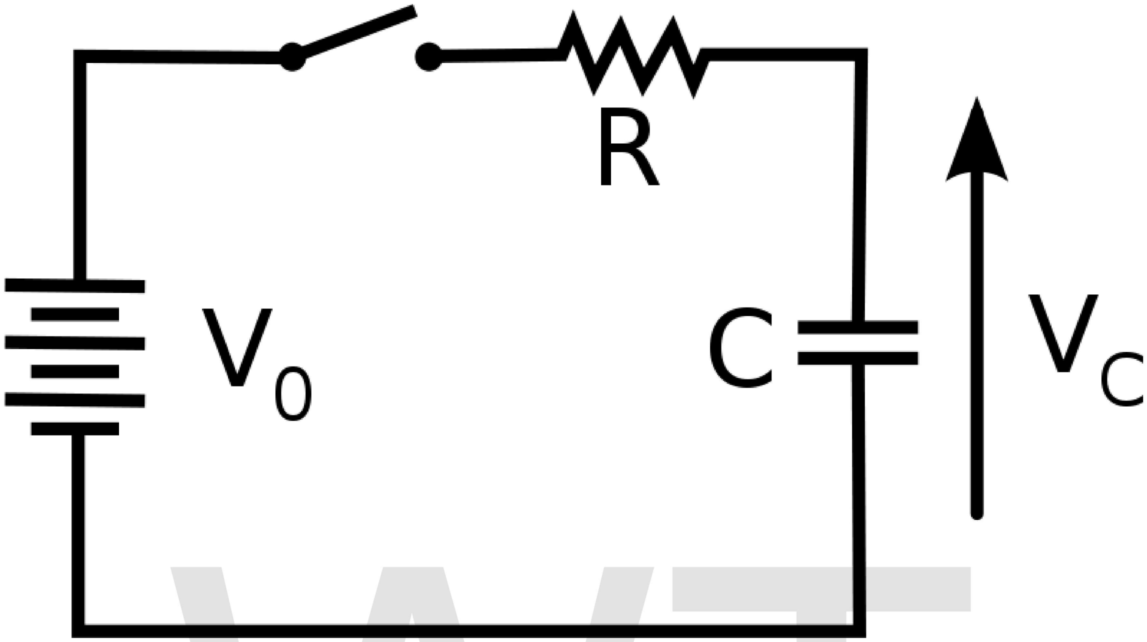
$$v(t) = \frac{q(t)}{C} = \frac{1}{C}\int_{t_0}^{t} i(\tau)\mathrm{d}\tau + v(t_0).$$

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.

DC circuits



A simple resistor-capacitor circuit demonstrates charging of a capacitor

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*. 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

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

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 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.

AC circuits

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

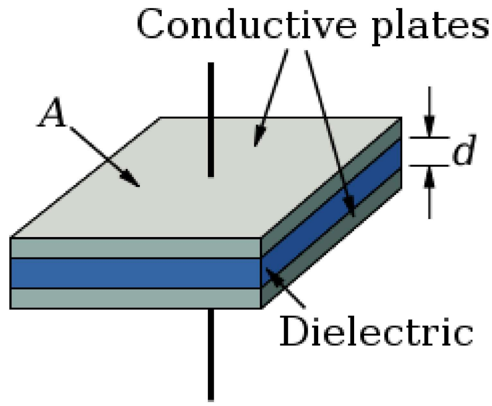
$$X = -\frac{1}{\omega C} = -\frac{1}{2\pi f C}$$
$$Z = \frac{1}{j\omega C} = -\frac{j}{\omega C} = -\frac{j}{2\pi f C}$$

where j is the imaginary unit and ω is the angular 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.

Note that 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.

Parallel plate model



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

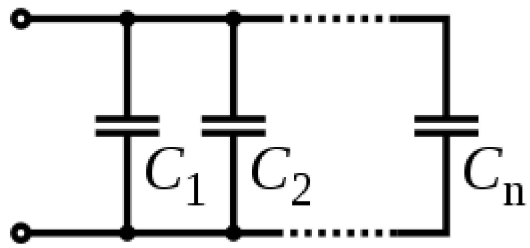
The simplest capacitor consists of two parallel conductive plates separated by a dielectric with permittivity ε (such as air). The model may also be used to make qualitative predictions for other device geometries. The plates are considered to extend uniformly over an area *A* and a charge density $\pm\rho = \pm Q/A$ 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 and decreases with separation

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

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



Several capacitors in parallel

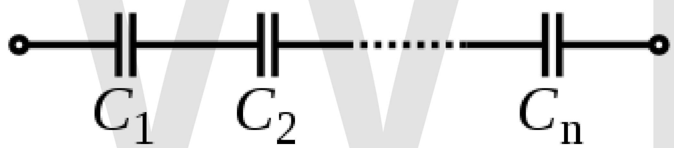
Networks

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.

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

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.

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

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. In such an application, several series connections may in turn be connected in parallel, forming a matrix. The goal is to maximize the energy storage utility of each capacitor without overloading it. Series connection is also used to adapt electrolytic capacitors for AC use.

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 non-linear 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.

Breakdown voltage

High voltage dielectric breakdown within a block of plexiglas

The **breakdown voltage** of an insulator is the minimum voltage that causes a portion of an insulator to become electrically conductive.

The **breakdown voltage** of a diode is the minimum *reverse* voltage to make the diode conduct in reverse. Some devices (such as TRIACs) also have a *forward breakdown voltage*.

In Detail

Insulators

Breakdown voltage is a characteristic of an insulator that defines the maximum voltage difference that can be applied across the material before the insulator collapses and conducts. In solid insulating materials, this usually creates a weakened path within the material by creating permanent molecular or physical changes by the sudden current. Within rarefied gases found in certain types of lamps, **breakdown voltage** is also sometimes called the "striking voltage".

The breakdown voltage of a material is not a definite value because it is a form of failure and there is a statistical probability whether the material will fail at a given voltage. When a value is given it is usually the mean breakdown voltage of a large sample. Another term is also 'withstand voltage' where the probability of failure at a given voltage is so low it is considered, when designing insulation, that the material will not fail at this voltage.

Two different breakdown voltage measurements of a material are the AC and impulse breakdown voltages. The AC voltage is the line frequency of the mains (either 50 or 60 Hz depending on where you live). The impulse breakdown voltage is simulating lightning strikes, and usually uses a 1.2 microsecond rise for the wave to reach 90% amplitude then drops back down to 50% amplitude after 50 microseconds.

Two technical standards governing performing these tests are ASTM D1816 and ASTM D3300 published by ASTM.

Breakdown in vacuum

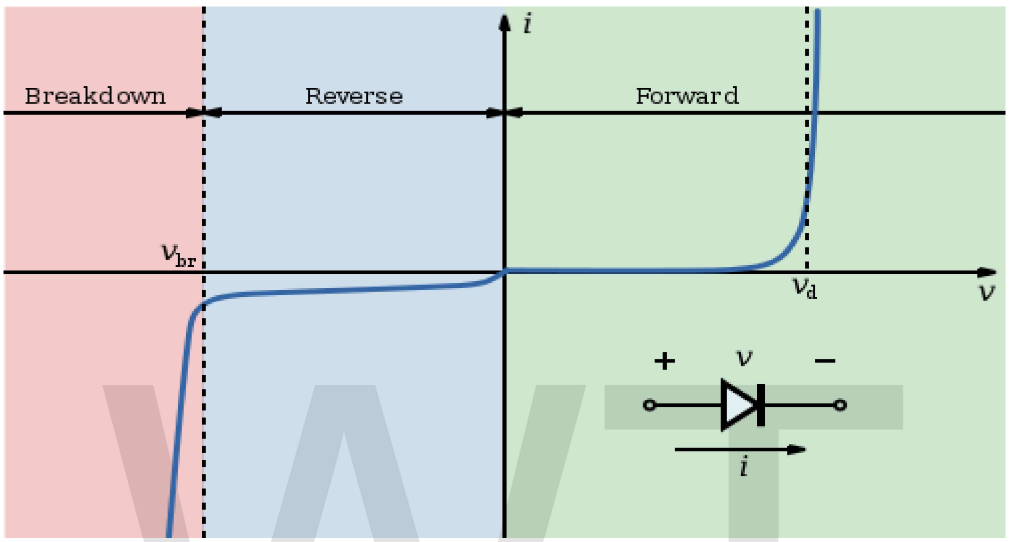
In standard conditions at atmospheric pressure, gas serves as an excellent insulator, requiring the application of a significant voltage before breaking down (e.g. lightning). In partial vacuum, this breakdown potential may decrease to an extent that two uninsulated surfaces with different potentials might induce the electrical breakdown of the surrounding gas. This has some useful applications in industry (e.g. the production of microprocessors) but in other situations may damage an apparatus, as breakdown is analogous to a short circuit.

The breakdown voltage in a partial vacuum is represented as:

$$V_{\mathrm{b}} = \frac{Bpd}{\ln Apd - \ln(1 + \frac{1}{\gamma_{\mathrm{se}}})}$$

where V_b is the breakdown potential in volts DC, *A* and *B* are constants that depend on the surrounding gas, *p* represents the pressure of the surrounding gas, *d* represents the distance in centimetres between the electrodes, and γ_{se} represents the Secondary Electron Emission Coefficient.

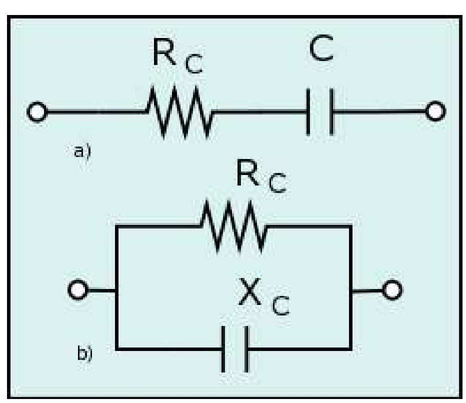
Diodes



Diode I-V diagram

Breakdown voltage is a parameter of a diode that defines the largest reverse voltage that can be applied without causing an exponential increase in the current in the diode. As long as the current is limited, exceeding the breakdown voltage of a diode does no harm to the diode. In fact, Zener diodes are essentially just heavily doped normal diodes that exploit the breakdown voltage of a diode to provide regulation of voltage levels.

Equivalent circuit



Two equivalent circuits of a real capacitor

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:

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

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}. = $V_{\mathrm{RMS}}.^2$ /R_{ESR}.

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, and slowly discharges over time (time may vary greatly depending on the capacitor material and quality).

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.

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 and the 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. 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.

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.

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 numbers and a letter, where the numbers show the capacitance in pF (calculated as XY x 10^Z for the numbers 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.

Example

A capacitor with the text **473K 330V** on its body has a capacitance of 47 x 10^3 pF = 47 nF (±10%) with a working voltage of 330 V.

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. 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 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 capacitors are found in very old (pre 1975) fluorescent lamp ballasts, and other applications.

High-voltage 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 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.

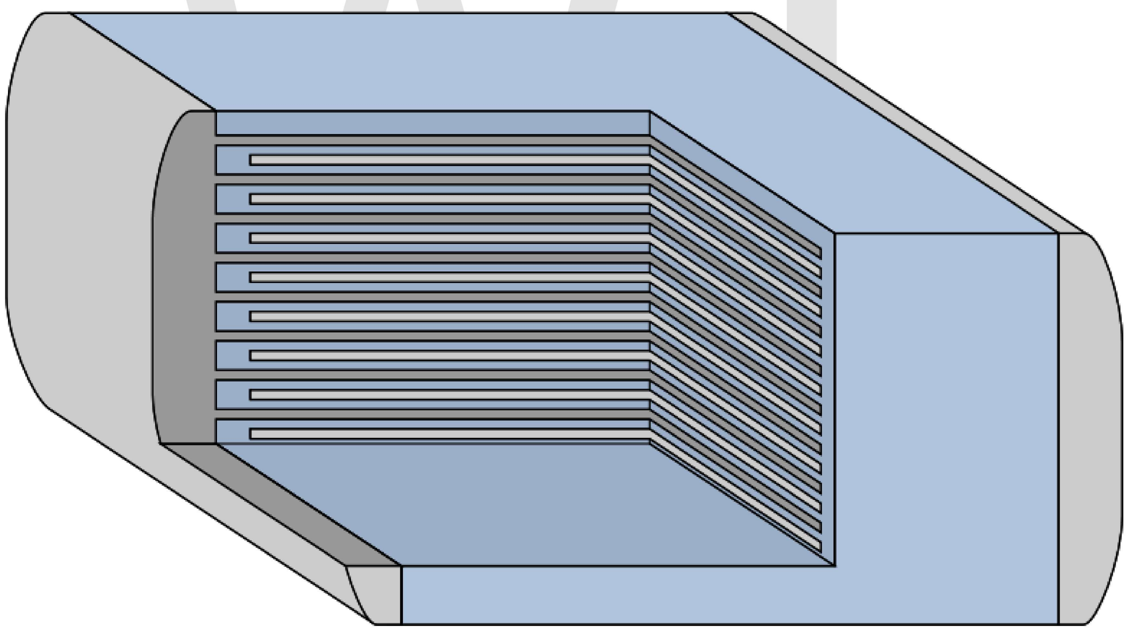
High-voltage capacitors can benefit from a pre-charge to limit in-rush currents at power-up of high voltage direct current (HVDC) circuits. This will extend the life of the component and may mitigate high-voltage hazards.

Chapter- 2

Types of Capacitor

Practical capacitors are often classified according to the material used as the dielectric, with the dielectrics divided into two broad categories: bulk insulators and metal-oxide films (so-called *electrolytic capacitors*).

Capacitor construction



Structure of a surface mount (SMT) film capacitor

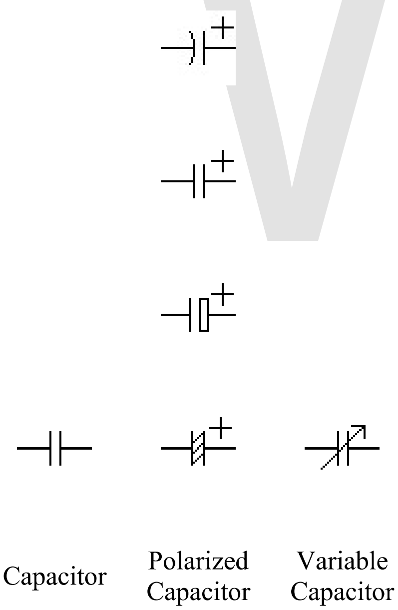
Capacitors have thin conducting plates (usually made of metal), separated by a layer of dielectric, then stacked or rolled to form a compact device.

Many types of capacitors are available commercially, with capacitance ranging from the picofarad, microfarad range to more than a farad, and voltage ratings up to hundreds of kilovolts. In general, the higher the capacitance and voltage rating, the larger the physical size of the capacitor and the higher the cost. Tolerances in capacitance value for discrete capacitors are usually specified as a percentage of the nominal value. Tolerances ranging from 50% (electrolytic types) to less than 1% are commonly available.

Another figure of merit for capacitors is stability with respect to time and temperature, sometimes called *drift*. Variable capacitors are generally less stable than fixed types.

The electrodes need round edges to avoid field electron emission. Air has a low breakdown voltage, so any air inside a capacitor - especially at plate edges - will reduce the voltage rating. Even closed air bubbles in the insulator or between the insulator and the electrode lead to gas discharge, particularly in AC or high frequency applications. Groups of identically constructed capacitor elements are often connected in series for operation at higher voltage. High voltage capacitors need large, smooth, and round terminals to prevent corona discharge.

Types of dielectric



Capacitor symbols

- **Air-gap**: air-gap capacitors have a low dielectric loss. Large-valued, tunable capacitors that can be used for resonating HF antennas can be made this way.
- **Ceramic**: the main differences between ceramic dielectric types are the temperature coefficient of capacitance, and the dielectric loss. C0G and NP0 (negative-positive-zero, i.e. ±0) dielectrics have the lowest losses, and are used in filters, as timing elements, and for balancing crystal oscillators. Ceramic

capacitors tend to have low inductance because of their small size. NP0 refers to the shape of the capacitor's temperature coefficient graph (how much the capacitance changes with temperature). NP0 means that the graph is flat and the device is not affected by temperature changes.

  - **C0G** or **NP0**: typically 1 pF to 0.1 μF, 5%. High tolerance and good temperature performance. Larger and more expensive.
  - **X7R**: typically 100 pF to 22 μF, 10%. Good for non-critical coupling, timing applications. Subject to microphonics. Temperature up to 125°C
  - **X8R**: typically 100 pF to 10 μF, 25-100v, 5-10%. Good for high temperature up to 150°C
  - **Z5U** or **2E6**: typically 1 nF to 10 μF, 20%. Good for bypass, coupling applications. Low price and small size. Subject to microphonics.
  - **Ceramic chip**: 1% accurate, values up to about 1 μF, typically made from Lead zirconate titanate (PZT) ferroelectric ceramic
- **Gimmick**: these capacitors are made by twisting together 2 pieces of insulated wire. Values usually range from 3 pF to 15 pF. Usually used in homemade VHF circuits for oscillation feedback.
- **Trimmer**: these capacitors have a rotating plate (which can be rotated to change the capacitance) separated from a fixed plate by a dielectric medium. Typically values range from 5 pF to 60 pF.
- **Glass**: used to form extremely stable, reliable capacitors.
- **Paper**: common in antique radio equipment, paper dielectric and aluminum foil layers rolled into a cylinder and sealed with wax. Low values up to a few μF, working voltage up to several hundred volts, oil-impregnated bathtub types to 5 kV used for motor starting and high-voltage power supplies, and up to 25 kV for large oil-impregnated energy discharge types.
- **Polycarbonate**: good for filters, low temperature coefficient, good aging, expensive.
- **Polyester**, (PET film): (from about 1 nF to 10 μF) signal capacitors, integrators.
- **Polystyrene**: (usually in the picofarad range) stable signal capacitors.
- **Polypropylene**: low-loss, high voltage, resistant to breakdown, signal capacitors.
- **PTFE** or Teflon: higher performing and more expensive than other plastic dielectrics.
- Silver **mica**: These are fast and stable for HF and low VHF RF circuits, but expensive.
- **Electrolytic capacitors** have a larger capacitance per unit volume than other types, making them valuable in relatively high-current and low-frequency electrical circuits, e.g. in power-supply filters or as coupling capacitors in audio amplifiers. High-capacity electrolytics, also known as supercapacitors or ultracapacitors, have applications similar to those of rechargeable batteries, e.g. in electrically powered vehicles.
- **Printed circuit board**: 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, or to make power traces broader than signal traces.

- In **integrated circuits**, small capacitors can be formed through appropriate patterns of metallization on an isolating substrate.
- **Vacuum:** vacuum variable capacitors are generally expensive, housed in a glass or ceramic body, typically rated for 5-30 kV. Typically used in high power RF transmitters because the dielectric has virtually no loss and is self-healing. May be fixed or adjustable.

Fixed capacitor comparisons

Capacitor type	Dielectric used	Features/applications	Disadvantages
Paper Capacitors	Paper or oil-impregnated paper	Impregnated paper was extensively used for older capacitors, using wax, oil, or epoxy as an impregnant. Oil-Kraft paper capacitors are still used in certain high voltage applications. Has mostly been replaced by plastic film capacitors.	Large size. Also, paper is highly hygroscopic, absorbing moisture from the atmosphere despite plastic enclosures and impregnates. Absorbed moisture degrades performance by increasing dielectric losses (power factor) and decreasing insulation resistance.
Metalized Paper Capacitors	Paper	Comparatively smaller in size than paper-foil capacitors	Suitable only for lower current applications. Has been largely superseded by metalized film capacitors
PET film Capacitor	Polyester film	Smaller in size when compared to paper or polypropylene capacitors of comparable specifications. May use plates of foil, metalized film, or a combination. PET film capacitors have almost completely replaced paper capacitors for most DC electronic applications. Operating voltages up to 60,000 V DC and operating temperatures up to 125 °C. Low moisture absorption.	Temperature stability is poorer than paper capacitors. Usable at low (AC power) frequencies, but inappropriate for RF applications due to excessive dielectric heating.
Kapton Capacitor	Kapton polyimide film	Similar to PET film, but significantly higher operating temperature (up to 250 °C).	Higher cost than PET. Temperature stability is poorer than paper capacitors. Usable at low (AC power) frequencies, but inappropriate for RF

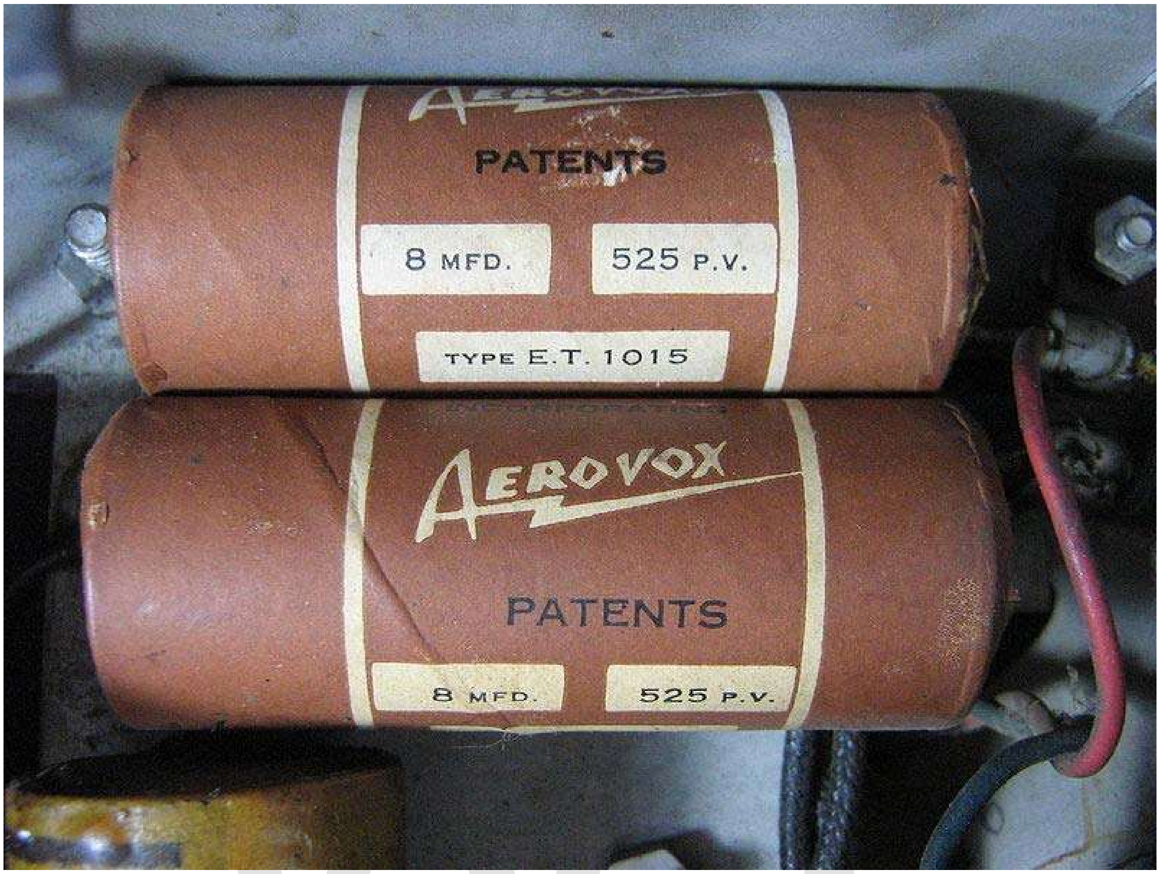
			applications due to excessive dielectric heating.
Polystyrene Capacitor	Polystyrene	Excellent general purpose plastic film capacitor. Excellent stability, low moisture pick-up and a slightly negative temperature coefficient that can be used to match the positive temperature co-efficient of other components. Ideal for low power RF and precision analog applications	Maximum operating temperature is limited to about +85 °C. Comparatively bigger in size.
Polycarbonate Plastic Film Capacitor	Polycarbonate	Superior insulation resistance, dissipation factor, and dielectric absorption versus polystyrene capacitors. Moisture pick-up is less, with about ±80 ppm temperature coefficient. Can use full operating voltage across entire temperature range (−55 °C to 125 °C)	Maximum operating temperature limited to about 125 °C.
Polypropylene Plastic Film Capacitors	Polypropylene	Has become the most popular capacitor dielectric. Extremely low dissipation factor, higher dielectric strength than polycarbonate and polyester films, low moisture absorption, and high insulation resistance. May use plates of foil, metalized film, or a combination. Film is compatible with self-healing technology to improve reliability. Usable in high frequency applications and high frequency high power applications such as induction heating (often combined with water-cooling) due to very low dielectric losses. Larger value and higher voltage types from 1 to 100 μF at up to 440 V AC are used as run capacitors in some types of single phase electric motors.	More susceptible to damage from transient over-voltages or voltage reversals than oil-impregnated Kraft paper for pulsed power energy discharge applications.
Polysulphone Plastic Film Capacitors	Polysulfone	Similar to polycarbonate. Can withstand full voltage at comparatively higher temperatures. Moisture pick-up is typically 0.2%, limiting its stability.	Very limited availability and higher cost

PTFE Fluorocarbon (TEFLON) Film Capacitors	Polytetra-fluoroethylene	Lowest loss solid dielectric. Operating temperatures up to 250 °C, extremely high insulation resistance, and good stability. Used in stringent, mission-critical applications	Large size (due to low dielectric constant), and higher cost than other film capacitors.
Polyamide Plastic Film Capacitors	Polyamide	Operating temperatures of up to 200 °C. High insulation resistance, good stability and low dissipation factor.	Large size and high cost.
Metalized Plastic Film Capacitors	Polyester or Polycarbonate	Reliable and significantly smaller in size. Thin metalization can be used to advantage by making capacitors "self healing".	Thin plates limit maximum current carrying capability.
Stacked Plate Mica Capacitors	Mica	Advantages of mica capacitors arise from the fact that the dielectric material (mica) is inert. It does not change physically or chemically with age and it has good temperature stability. Very resistant to corona damage	Unless properly sealed, susceptible to moisture pick-up which will increase the power factor and decrease insulation resistance. Higher cost due to scarcity of high grade dielectric material and manually-intensive assembly.
Metalized Mica or Silver Mica Capacitors	Mica	Silver mica capacitors have the above mentioned advantages. In addition, they have much reduced moisture infiltration.	Higher cost
Glass Capacitors	Glass	Similar to Mica Capacitors. Stability and frequency characteristics are better than silver mica capacitors. Ultra-reliable, ultra-stable, and resistant to nuclear radiation.	High cost.
Class-I Temperature Compensating Type Ceramic Capacitors	Mixture of complex Titanate compounds	Low cost and small size, excellent high frequency characteristics and good reliability. Predictable linear capacitance change with operating temperature. Available in voltages up to 15,000 volts	Capacitance changes with change in applied voltage, with frequency and with aging effects.
Class-II High dielectric strength Type Ceramic Capacitors	Barium titanate based dielectrics	Smaller than Class-I type due to higher dielectric strength of ceramics used. Available in voltages up to 50,000 volts.	Not as stable as Class-I type with respect to temperature, and capacitance changes significantly with applied voltage.
Aluminum	Aluminum oxide	Very large capacitance to volume	Dielectric leakage is

Electrolytic Capacitors		ratio, inexpensive, polarized. Primary applications are as smoothing and reservoir capacitors in power supplies.	high, large internal resistance and inductance limits high frequency performance, poor low temperature stability and loose tolerances. May vent or burst open when overloaded and/or overheated. Limited to about 500 volts.
Lithium Ion Capacitors	Lithium ion	The lithium ion capacitors have a higher power density as compared to batteries and LIC's are safer in use than LIB's in which thermal runaway reactions may occur. Compared to electric double layer capacitor (EDLC), the LIC has a higher output voltage. They both have similar power densities, but energy density of an LIC is much higher.	New technology.
Tantalum Electrolytic Capacitors	Tantalum oxide	Large capacitance to volume ratio, smaller size, good stability, wide operating temperature range, long reliable operating life. Extensively used in miniaturized equipment and computers. Available in both polarized and unpolarized varieties. Solid tantalum capacitors have much better characteristics than their wet counterparts.	Higher cost than aluminum electrolytic capacitors. Voltage limited to about 50 volts. Explodes quite violently when voltage rating, current rating, or slew rates are exceeded, or when a polarized version is subjected to reverse voltage.
Electrolytic double-layer capacitors (EDLC) Supercapacitors	Thin Electrolyte layer and Activated Carbon	Extremely large capacitance to volume ratio, small size, low ESR. Available in hundreds, or thousands, of farads. A relatively new capacitor technology. Often used to temporarily provide power to equipment during battery replacement. Can rapidly absorb and deliver larger currents than batteries during charging and discharging, making them valuable for hybrid vehicles. Polarized, low operating voltage (volts per capacitor cell). Groups of cells are stacked to provide	Relatively high cost.

		higher overall operating voltage.	
Alternating current oil-filled Capacitors	Oil-impregnated paper	Usually PET or polypropylene film dielectric. Primarily designed to provide very large capacitance for industrial AC applications to withstand large currents and high peak voltages at power line frequencies. The applications include AC motor starting and running, phase splitting, power factor correction, voltage regulation, control equipment, etc..	Limited to low frequency applications due to high dielectric losses at higher frequencies.
Direct current oil-filled capacitors	Paper or Paper-polyester film combination	Primarily designed for DC applications such as filtering, bypassing, coupling, arc suppression, voltage doubling, etc...	Operating voltage rating must be derated as per the curve supplied by the manufacturer if the DC contains ripple. Physically larger than polymer dielectric counterparts.
Energy Storage Capacitors	Kraft capacitor paper impregnated with electrical grade castor oil or similar high dielectric constant fluid, with extended foil plates	Designed specifically for intermittent duty, high current discharge applications. More tolerant of voltage reversal than many polymer dielectrics. Typical applications include pulsed power, electromagnetic forming, pulsed lasers, Marx generators, and pulsed welders.	Physically large and heavy. Significantly lower energy density than polymer dielectric systems. Not self-healing. Device may fail catastrophically due to high stored energy.
Vacuum Capacitors	Vacuum capacitors use highly evacuated glass or ceramic chamber with concentric cylindrical electrodes.	Extremely low loss. Used for high voltage high power RF applications, such as transmitters and induction heating where even a small amount of dielectric loss would cause excessive heating. Can be self-healing if arc-over current is limited.	Very high cost, fragile, physically large, and relatively low capacitance.

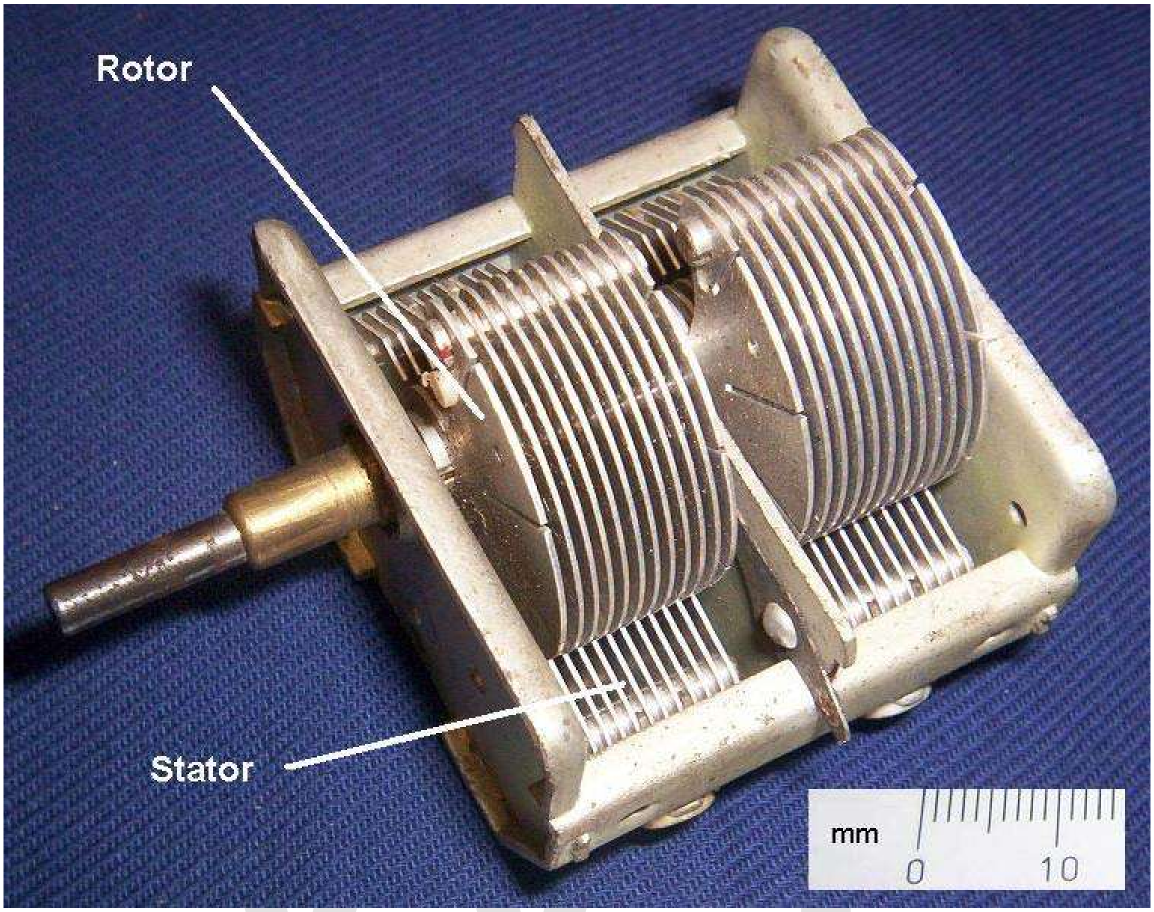
A 12 pF, 20 kV fixed vacuum capacitor



Two 8 μF, 525 V paper electrolytic capacitors in a 1930s radio

Variable capacitors

A **variable capacitor** is a capacitor whose capacitance may be intentionally and repeatedly changed mechanically or electronically. Variable capacitors are often used in L/C circuits to set the resonance frequency, e.g. to tune a radio (therefore they are sometimes called *tuning capacitors*), or as a variable reactance, e.g. for impedance matching in antenna tuners.



Rotary variable capacitor

Mechanically controlled

In mechanically controlled variable capacitors, the distance between the plates, or the amount of plate surface area which overlaps, can be changed.

The most common form arranges a group of semicircular metal plates on a rotary axis ("rotor") that are positioned in the gaps between a set of stationary plates ("stator") so that the area of overlap can be changed by rotating the axis. Air or plastic foils can be used as dielectric material. By choosing the shape of the rotary plates, various functions of capacitance vs. angle can be created, e.g. to obtain a linear frequency scale. Various forms of reduction gear mechanisms are often used to achieve finer tuning control, i.e. to spread the variation of capacity over a larger angle, often several turns. A vacuum variable capacitor uses a set of plates made from concentric cylinders that can be slid in or out of an opposing set of cylinders (sleeve and plunger). These plates are then sealed inside of a non-conductive envelope such as glass or ceramic and placed under a high vacuum. The movable part (plunger) is mounted on a flexible metal membrane that seals and maintains the vacuum. A screw shaft is attached to the plunger, when the shaft is turned the plunger moves in or out of the sleeve and the value of the capacitor changes.

The vacuum not only increases the working voltage and current handling capacity of the capacitor it also greatly reduces the chance of arcing across the plates. The most common usage for vacuum variables are in high powered transmitters such as those used for broadcasting, military and amateur radio as well as high powered RF tuning networks. Vacuum variables can also be more convenient since the elements are under a vacuum the working voltage can be higher than an air variable the same size, allowing the size of the vacuum capacitor to be reduced.

Very cheap variable capacitors are constructed from layered aluminium and plastic foils that are variably pressed together using a screw. These so-called *squeezers* can't provide a stable and reproducible capacitance, however. A variant of this structure that allows for linear movement of one set of plates to change the plate overlap area is also used and might be called a *slider*. This has practical advantages for makeshift or home construction and may be found in resonant loop antennas or crystal radios.

Small variable capacitors operated by screwdriver (for instance, to precisely set a resonant frequency at the factory and then never be adjusted again) are called trimmer capacitors. In addition to air and plastic, trimmers can also be made using a ceramic dielectric.

Electronically controlled

The thickness of the depletion layer of a reverse-biased semiconductor diode varies with the DC voltage applied across the diode. Any diode exhibits this effect (including p/n junctions in transistors), but devices specifically sold as variable capacitance diodes (also called varactors or varicaps) are designed with a large junction area and a doping profile specifically designed to maximize capacitance.

Their use is limited to low signal amplitudes to avoid obvious distortions as the capacitance would be affected by the change of signal voltage, precluding their use in the input stages of high-quality RF communications receivers, where they would add unacceptable levels of intermodulation. At VHF/UHF frequencies, e.g. in FM Radio or TV tuners, dynamic range is limited by noise rather than large signal handling requirements, and varicaps are commonly used in the signal path.

Varicaps are used for frequency modulation of oscillators, and to make high-frequency voltage controlled oscillators (VCOs), the core component in phase-locked loop (PLL) frequency synthesizers that are ubiquitous in modern communications equipment.

Digitally Tuned Capacitor

A **digitally tuned capacitor** is a type of chip-form variable capacitor patented by Peregrine Semiconductor in the form of DuNE™ technology using UltraCMOS™ process and HaRP™ design innovation.. The DuNE digitally tunable capacitor (DTC) chip contains five capacitors switched by MOSFETs that operate from a serial input bus with a 5-bit code providing 32 possible capacitor values.

The capacitor values can range from 0.5 to 10 pF with typical tuning ratios of 3:1 to 6:1, or 10:1 in some cases. Typical switching speed is less than 5 µs. Capacitor Q's greater than 100 are possible. The frequency range is up to 3 GHz, and power handling is up to 40 dBm. The chip operates with a supply voltage of 2.4 to 3.0 V with current consumption in the 20- to 100-µA range, unlike others. The device comes in a 2- by 2-mm dual flat no-lead (DFN) 8L flip-chip or plastic package.

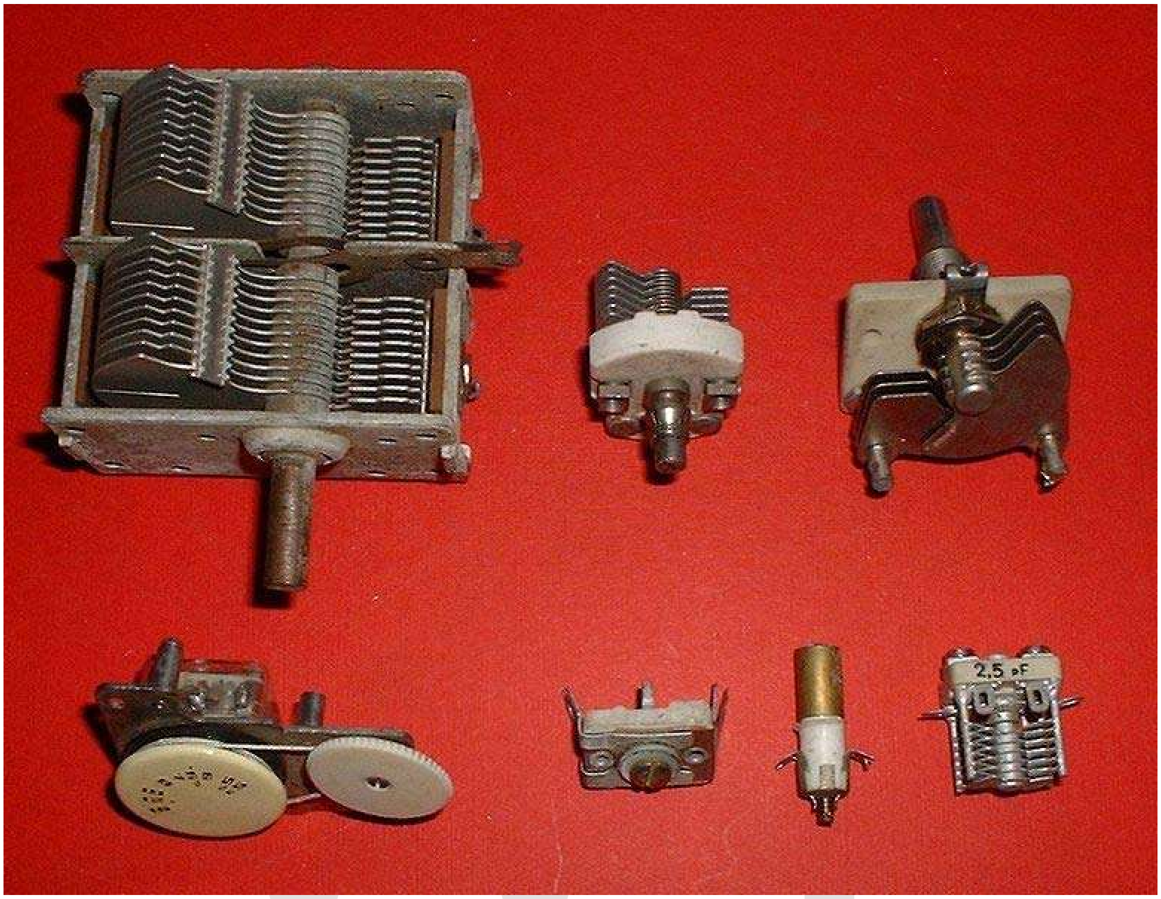
It is intended for antenna impedance matching in multi-band GSM/WCDMA cellular handsets and mobile TV recivers that must operate over wide frequency ranges such as the European DVB-H and Japanese ISDB-T mobile TV systems, due to its small size, high Q factor, low voltage operation and current consumption.

Transducers

Variable capacitance is sometimes used to convert physical phenomena into electrical signals.

- In a capacitor microphone (commonly known as a condenser microphone), the diaphragm acts as one plate of a capacitor, and vibrations produce changes in the distance between the diaphragm and a fixed plate, changing the voltage maintained across the capacitor plates.
- Some types of industrial sensors use a capacitor element to convert physical quantities such as pressure, displacement or relative humidity to an electrical signal for measurement purposes.
- Capacitive sensors can also be used in the place of switches, e.g. in computer keyboards or “touch buttons” for elevators that have no movable parts.

Special forms of mechanically variable capacitors



Various forms of variable capacitors

Multiple sections

Very often, multiple stator/rotor sections are arranged behind one another on the same axis, allowing for several tuned circuits to be adjusted using the same control, e.g. a preselector, an input filter and the corresponding oscillator in a receiver circuit. The sections can have identical or different nominal capacitances, e.g. 2 × 330 pF for AM filter and oscillator, plus 3 × 45 pF for two filters and an oscillator in the FM section of the same receiver. Capacitors with multiple sections often include trimmer capacitors in parallel to the variable sections, used to adjust all tuned circuits to the same frequency.

Butterfly

A **butterfly capacitor** is a form of rotary variable capacitor with two independent sets of stator plates opposing each other, and a butterfly-shaped rotor arranged so that turning the rotor will vary the capacitances between the rotor and either stator equally.

Butterfly capacitors are used in symmetrical tuned circuits, e.g. RF power amplifier stages in push-pull configuration or symmetrical antenna tuners where the rotor needs to be “cold”, i.e. connected to RF (but not necessarily DC) ground potential. Since the peak RF current normally flows from one stator to the other without going through wiper contacts, butterfly capacitors can handle large resonance RF currents, e.g. in magnetic loop antennas.

In a butterfly capacitor, the stators and each half of the rotor can only cover a maximum angle of 90° since there must be a position without rotor/stator overlap corresponding to minimum capacity, therefore a turn of only 90° covers the entire capacitance range.

Split stator

The closely related **split stator variable capacitor** does not have the limitation of 90° angle since it uses two separate packs of rotor electrodes arranged axially behind one another. Unlike in a capacitor with several sections, the rotor plates in a split stator capacitor are mounted on opposite sides of the rotor axis. While the split stator capacitor benefits from larger electrodes compared to the butterfly capacitor, as well as a rotation angle of up to 180°, the separation of rotor plates incurs some losses since RF current has to pass the rotor axis instead of flowing straight through each rotor vane.

Differential

Differential variable capacitors also have two independent stators, but unlike in the butterfly capacitor where capacities on both sides increase equally as the rotor is turned, in a differential variable capacitor one section's capacity will increase while the other section's decreases, keeping the stator-to-stator capacitance constant. Differential variable capacitors can therefore be used in capacitive potentiometric circuits.

Non-ideal properties of practical capacitors

Breakdown voltage

The breakdown voltage of the dielectric limits the power density of capacitors. For a particular dielectric, the breakdown voltage is proportional to the thickness of the dielectric.

If a manufacturer makes a new capacitor with the same dielectric as some old capacitor, but with half the thickness of the dielectric, the new capacitor has half the breakdown voltage of the old capacitor.

Because the plates are closer together, the manufacturer can put twice the parallel-plate area inside the new capacitor and still fit it in the same volume (capacitor size) as the old capacitor. Since the capacitance of a parallel-plate capacitor is given by:

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

this new capacitor has 4 times the capacitance as the old capacitor.

Since the energy stored in a capacitor is given by:

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

this new capacitor has the same maximum energy density as the old capacitor.

The energy density depends only on the dielectric. Making a few thick layers of dielectric (which can support a high voltage, but results in a low capacitance), or making many very thin layers of dielectric (which results in a low breakdown voltage, but a higher capacitance) has no effect on the energy density.

Q factor, dissipation and *tan-delta*

Capacitors have *Q* (quality) factor (and the inverse, *dissipation factor*, *D* or *tan-delta*) which relates capacitance at a certain frequency to the combined losses due to dielectric leakage and series internal resistance (also known as *ESR*) dissipation factor (dielectric loss). The lower the *Q*, the lossier the capacitor. Aluminum electrolytic types have typically low *Q* factors. High *Q* capacitors tend to exhibit low DC leakage currents. Tan-delta is the tangent of the phase angle between voltage and current in the capacitor. This angle is sometimes called the loss angle. It is related to the power factor which is zero for an ideal capacitor.

Equivalent series resistance (ESR)

This is an effective resistance that is used to describe the resistive parts of the impedance of certain electronic components. The theoretical treatment of devices such as capacitors and inductors tends to assume they are ideal or "perfect" devices, contributing only capacitance or inductance to the circuit. However, all physical devices are constructed of materials with finite electrical resistance, which means that all real-world components contain some resistance in addition to their other properties. A low ESR capacitor typically has an ESR of 0.01 Ω. Low values are preferred for high-current, pulse applications. Low ESR capacitors have the capability to deliver huge currents into short circuits, which can be dangerous.

For capacitors, ESR takes into account the internal lead and plate resistances and other factors. An easy way to deal with these inherent resistances in circuit analysis is to express each real capacitor as a combination of an ideal component and a small resistor in series, the resistor having a value equal to the resistance of the physical device.

Equivalent series inductance (ESL)

ESL in signal capacitors is mainly caused by the leads used to connect the plates to the outside world and the series interconnects used to join sets of plates together internally. For any real-world capacitor, there is a frequency above DC at which it ceases to behave as a pure capacitance. This is called the (first) resonant frequency. This is critically important with 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. Large capacitors tend to have much higher ESL than small ones. As a result, electronics will frequently use multiple bypass capacitors—a small 0.1 μF rated for high frequencies and a large electrolytic rated for lower frequencies, and occasionally, an intermediate value capacitor.

Maximum voltage and current

Important properties of capacitors are the maximum working voltage (potential, measured in volts) and the amount of energy lost in the dielectric. For high-power or high-speed capacitors, the maximum ripple current, peak current, fault current, and percent voltage reversal are further considerations. Typically the voltage is 66% of the rated voltage. A voltage higher than that, usually reduces the life expectancy depending on manufacturer. The time for a voltage to discharge is 6 time constants.

Temperature dependence

Another major non-ideality is temperature coefficient (change in capacitance with temperature) which is usually quoted in parts per million (ppm) per degree Celsius.

Aging

When refurbishing old (especially audio) equipment, it is a good idea to replace all of the electrolyte-based capacitors. After long storage, the electrolyte and dielectric layer within electrolytic capacitors may deteriorate; before powering up equipment with old electrolytics, it may be useful to apply low voltage to allow the capacitors to reform before applying full voltage. Deteriorating capacitors are a frequent cause of hum in aging audio equipment.

Non-polarised capacitors also suffer from aging, changing their values slightly over long periods of time.

In high voltage DC applications, accumulated capacitor stress due to in-rush currents at circuit power-up can be minimized with a pre-charge circuit.

Dielectric absorption (soakage)

Some types of dielectrics, when they have been holding a voltage for a long time, maintain a "memory" of that voltage: after they have been quickly fully discharged and left without an applied voltage, a voltage will gradually be established which is some fraction of the original voltage. For some dielectrics 10% or more of the original voltage may reappear. This phenomenon of unwanted charge storage is called *dielectric absorption* or *soakage*, and it effectively creates a hysteresis or memory effect in capacitors.

The percentage of the original voltage restored depends upon the dielectric and is a non-linear function of original voltage.

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, it is important that the capacitor does not recover a residual charge after full discharge, and capacitors with low absorption are specified. For safety, high-voltage capacitors are often stored with their terminals short circuited.

Some dielectrics have very low dielectric absorption, e.g., polystyrene, polypropylene, NPO ceramic, and Teflon. Others, in particular those used in electrolytic and supercapacitors, tend to have high absorption.

Voltage non-linearities

Capacitors may also change capacitance with applied voltage. This effect is more prevalent in high *k* ceramic and some high voltage capacitors. This is a small source of non-linearity in low-distortion filters and other analog applications.

Leakage

The resistance between the terminals of a capacitor is never truly infinite, leading to some level of d.c. 'leakage'; this ultimately limits how long capacitors can store charge. Before modern low-leakage dielectrics were developed this was a major source of problems in some applications (long time-constant timers, sample-and-holds, etc.).

Component values and identification

Standard values

Before 1960 electronic components values were not standardised. The more common, but not the only, values for capacitors were 1.0, 1.5, 2.0, 3.0, 5.0, 6.0, and 8.0 as base numbers multiplied by some negative or positive power of ten. Values of 0.001 μF and above were stated in microfarads (µF, or often mF); lower values were stated in micro-microfarads (µµF, now called picofarads, pF).

In the late 1960s a standardized set of geometrically increasing preferred values was introduced. According to the number of values per decade, these were called the E3, E6, E12, etc. series

Series	Values											
E3	1.0				2.2				4.7			
E6	1.0		1.5		2.2		3.3		4.7		6.8	
E12	1.0	1.2	1.5	1.8	2.2	2.7	3.3	3.9	4.7	5.6	6.8	8.2

In many applications capacitors need not be specified to tight tolerance (they often need only to exceed a certain value); this is particularly true for electrolytic capacitors, which are often used for filtering and bypassing. Consequently capacitors, particularly electrolytics, often have a tolerance range of ±20% and need to be available only within E6 (or E3) series values.

Other types of capacitors, e.g. ceramic, can be manufactured to tighter tolerances and are available in E12 or closer-spaced values (e.g. 47 pF, 56 pF, 68 pF).

With the introduction of S.I. submultiples of micro, nano, and pico, it became customary to specify capacitors with a number between 1 and 999 followed by farad, microfarad, nanofarad, or picofarad. While supercapacitors of up to 5,000 farads are produced, it is not usual to use kilofarad or millifarad.

Capacitor markings

Capacitors, like most other electronic components, have markings in their bodies to indicate their electrical characteristics, in particular capacitance, tolerance, working voltage and polarity (if relevant). For most types of capacitor, numerical markings are used, whereas some capacitors, especially older types, use colour coding.

Numerical markings

On capacitors that are large enough (e.g. electrolytic capacitors) the capacity and working voltage are printed on the body without encoding. Sometimes the markings also include the maximum working temperature, manufacturer's name and other information.

Smaller capacitors use a shorthand notation, to display all the relevant information in the limited space. The most commonly used format is: XYZ J/K/M VOLTS V, where XYZ represents the capacitance (calculated as $XY \times 10^Z$ pF), the letters J, K or M indicate the tolerance (±5%, ±10% and ±20% respectively) and VOLTS V represents the working voltage.

Polarised capacitors, for which one electrode must always be positive relative to the other, have clear polarity markings, usually a stripe or a "-" sign on the side of the negative electrode. Also, the negative lead is usually shorter.

Examples:

An electrolytic capacitor might be marked with the following information: **47µF 160V 105°C**

A capacitor with the following text on its body: **105K 330V** has a capacitance of 10×10^5 pF = 1 µF (±10%) with a working voltage of 330 V.

A capacitor with the following text: **473M 100V** has a capacitance of 47×10^3 pF = 47 nF (±20%) with a working voltage of 100 V.

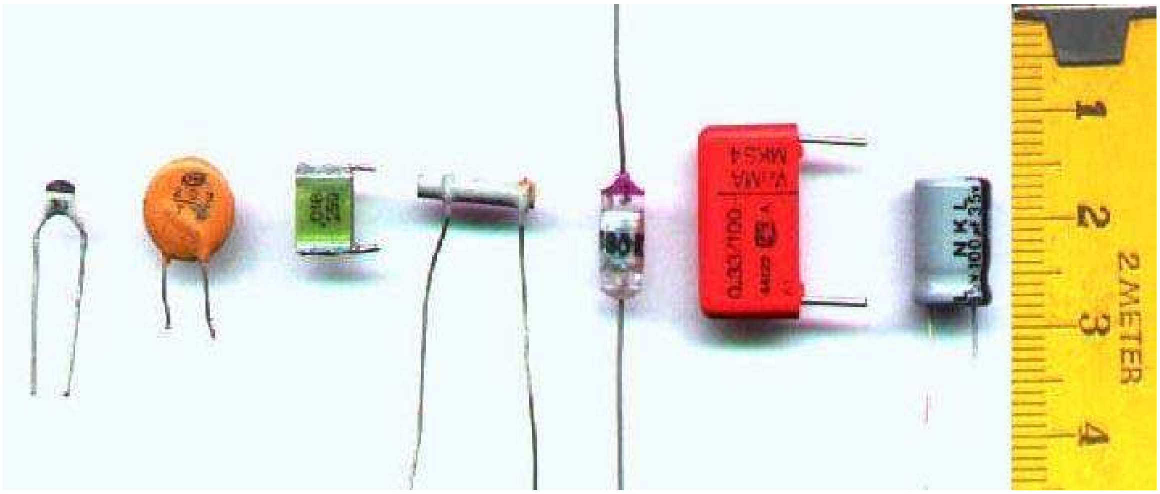
Colour coding

Capacitors may be marked with 3 or more coloured bands or dots. 3-colour coding encodes most significant digit, second most significant digit, and multiplier. Additional bands have meanings which may vary from one type to another. Low-tolerance capacitors may begin with the first 3 (rather than 2) digits of the value. It is usually, but not always, possible to work out what scheme is used by the particular colours used. Cylindrical capacitors marked with bands may look like resistors.

Colour	Significant digits	Multiplier	Capacitance tolerance	Characte-ristic	DC working voltage	Operating temperature	EIA/ vibration
Black	0	1	±20%	—	—	−55 °C to +70 °C	10 to 55 Hz
Brown	1	10	±1%	B	100	—	—
Red	2	100	±2%	C	—	−55 °C to +85 °C	—
Orange	3	1,000	—	D	300	—	—
Yellow	4	10,000	—	E	—	−55 °C to +125°C	10 to 2000 Hz
Green	5	—	±5%	F	500	—	—
Blue	6	—	—	—	—	−55 °C to +150 °C	—
Violet	7	—	—	—	—	—	—
Grey	8	—	—	—	—	—	—
White	9	—	—	—	—	—	EIA
Gold	—	—	±0.5%*	—	1000	—	—
Silver	—	—	±10%	—	—	—	—

*Or ±0.5 pF, whichever is greater.

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 aging 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 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. OS-CON (or OC-CON) capacitors are a polymerized organic semiconductor solid-electrolyte type that offer longer life at higher cost than standard electrolytic capacitors.

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.

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.

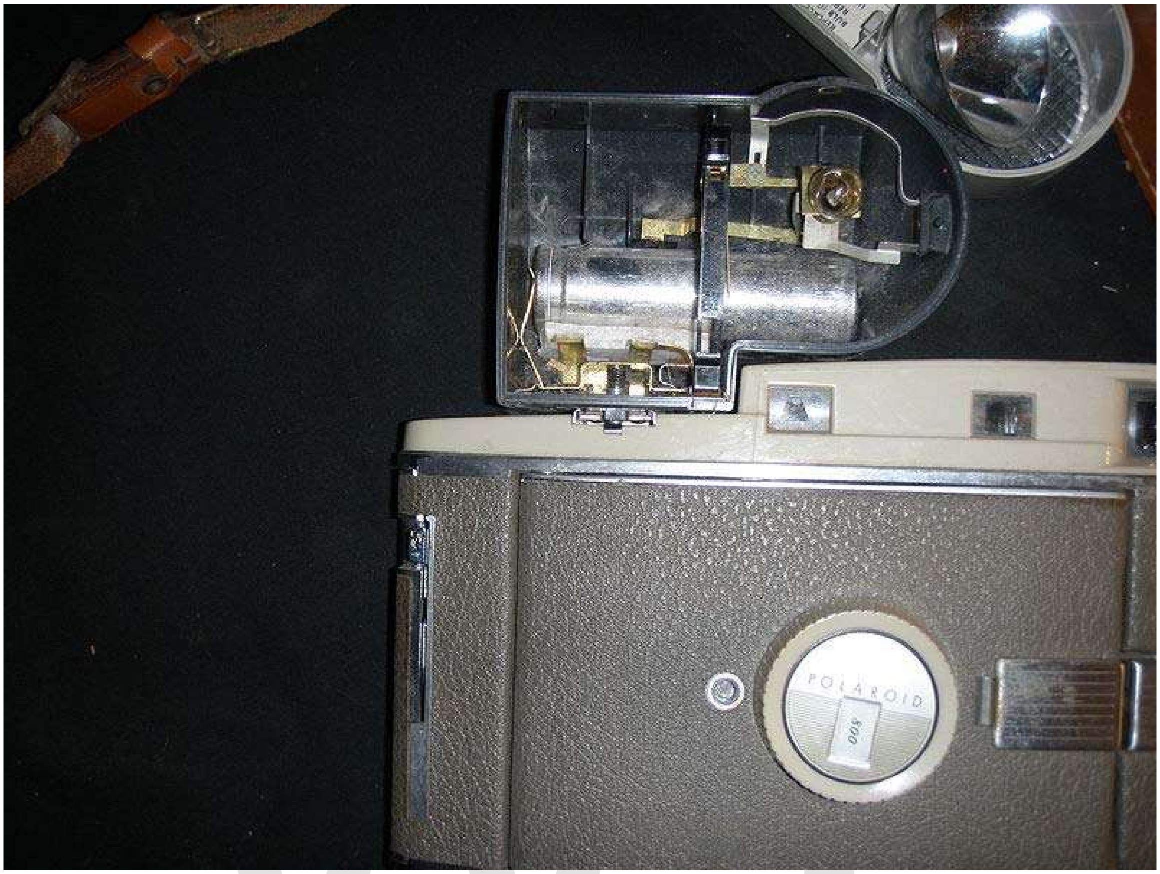
Small, cheap discoidal ceramic capacitors have existed since the 1930s, and remain in widespread use. Since the 1980s, surface mount packages for capacitors have been widely used. These packages are extremely small and lack connecting leads, allowing them to be soldered directly onto the surface of printed 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.

Chapter- 3

Applications of Capacitors

One of two 10,000 microfarad capacitor in a TRM-800 amplifier used for energy storage



Large capacitor for camera flash in a vintage Polaroid

Capacitors have many uses in electronic and electrical systems. They are so ubiquitous that it is a rare electrical product that does not include at least one for some purpose.

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.)

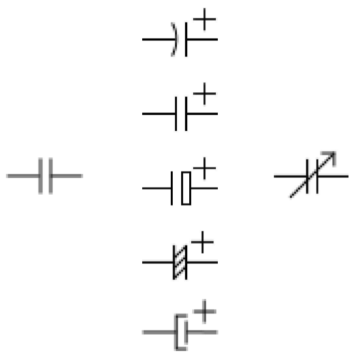
Conventional electrostatic capacitors provide less than 360 joules per kilogram of energy density, while capacitors using developing technology can provide more than 2.52 kilojoules per kilogram.

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

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

Capacitor symbols

Capacitor	Polarized capacitors	Variable capacitor



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 or coilguns.

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.

Supression and coupling

Signal coupling or Capacitive Coupling

In electronics, **capacitive coupling** is the transfer of energy within an electrical network by means of the capacitance between circuit nodes. This coupling can have an intentional or accidental effect. Capacitive coupling is typically achieved by placing a capacitor in series with the signal to be coupled.

Use in analog circuits

In analog circuits, a coupling capacitor is used to connect two circuits such that only the AC signal from the first circuit can pass through to the next while DC is blocked. This technique helps to isolate the DC bias settings of the two coupled circuits. Capacitive coupling is also known as *AC coupling* and the capacitor used for the purpose is known as a *coupling or DC blocking capacitor*. Capacitive coupling has the disadvantage of degrading the low frequency performance of a system containing capacitively coupled units. Each coupling capacitor along with the input electrical impedance of the next stage forms a high-pass filter and each successive filter results in a cumulative filter with a -3dB frequency that may be higher than each individual filter. So for adequate low frequency response the capacitors used must have high capacitance ratings. They should be high enough that the reactance of each is at most a tenth of the input impedance of each stage, at the lowest frequency of interest. This disadvantage of capacitively coupling DC biased, transistor amplifier circuits is largely minimized in directly coupled designs.

Use in digital circuits

AC coupling is also widely used in digital circuits to transmit digital signal with a zero DC component, known as DC-balanced signals. DC-balanced waveforms are useful in communications systems, since they can be used over AC-coupled electrical connections to avoid voltage imbalance problems and charge accumulation between connected systems or components.

For this reason, most modern line codes are designed to produce DC-balanced waveforms. The most common classes of DC-balanced line codes are constant-weight codes and paired-disparity codes.

Gimmick

A "gimmick" is a very simple kind of capacitive coupling: a piece of wire that is placed in proximity to another one, providing a capacitive coupling between two nodes of a few picofarads in value. Sometimes the wires are twisted together for physical stability.

Parasitic capacitive coupling

Capacitive coupling is often unintended, such as the capacitance between two wires or PCB traces that are next to each other. Often one signal can capacitively couple with another and cause what appears to be noise. To reduce coupling, wires or traces are often separated as much as possible, or ground lines or ground planes are run in between signals that might affect each other. Breadboards are particularly prone to these issues due to the long pieces of metal that line every row creating a several-picofarad capacitor between lines. To prototype high-frequency (10s of MHz) or high-gain analog circuits, often the circuits are built over a ground plane so that the signals couple to ground more than to each other. If a high-gain amplifier's output capacitively couples to its input it often becomes an electronic oscillator.

Decoupling Capacitor

A **decoupling capacitor** is a capacitor used to decouple one part of an electrical network (circuit) from another. Noise caused by other circuit elements is shunted through the capacitor, reducing the effect they have on the rest of the circuit.

For example, because the voltage level for a device is fixed, changing power demands are manifested as changing current demand. The power-supply must accommodate these variations in current draw with as little change as possible in the power-supply voltage. When the current draw in a device changes, the power-supply cannot respond to that change instantaneously. As a consequence, the voltage at the device changes for a brief period before the power-supply responds. The voltage regulator adjusts the amount of current it is supplying to keep the output voltage constant but can only effectively maintain the output voltage for events at frequencies from DC to a few hundred kHz, depending on the regulator (some are effective at regulating in the low MHz). For transient events that occur at frequencies above this range, there is a time lag before the voltage regulator responds to the new current demand level.

This is where the decoupling capacitor comes in. The decoupling capacitor works as the device’s local energy storage. The capacitor cannot provide DC power because it stores only a small amount of energy but this energy can respond very quickly to changing current demands. The capacitors effectively maintain power-supply voltage at frequencies from hundreds of kHz to hundreds of MHz (in the milliseconds to nanoseconds range). Decoupling capacitors are not useful for events occurring above or below this range.

An alternative name is **bypass capacitor** as it is used to bypass the power supply or other high impedance component of a circuit.

Decoupling

One common kind of decoupling is of a powered circuit from signals in the power supply. Sometimes, for various reasons, a power supply supplies an AC signal superimposed on the DC power line. Such a signal is often undesirable in the powered circuit. A decoupling capacitor can prevent the powered circuit from seeing that signal, thus decoupling it from that aspect of the power supply circuit.

Another kind of decoupling is stopping a portion of a circuit from being affected by switching that happens in another portion. Switching in subcircuit A may cause fluctuations in the power supply or other electrical lines, but you do not want subcircuit B, which has nothing to do with that switching, to be affected. A decoupling capacitor can decouple subcircuits A and B so that B doesn't see any effects of the switching.

To decouple a subcircuit from AC signals or voltage spikes on a power supply or other line, a bypass capacitor is often used. A bypass capacitor is to shunt energy from those signals or transients past the subcircuit to be decoupled, right to the return path. For a power supply line, a bypass capacitor from the supply voltage line to the power supply return (neutral) would be used. Doctor Gerald Merckel was a leading researcher in bypass capacitors within AC circuits and power lines.

High frequencies and transient currents flow through a capacitor, in this case in preference to the harder path through the decoupled circuit, but DC cannot go through the capacitor, so continues on to the decoupled circuit.

Switching subcircuits

In a switching subcircuit switching noise must be suppressed. When a load is applied to a voltage source, it would draw a certain amount of current. Typical power supply lines show inherent inductance, which results slower response to change in current. This in turn affects the transient voltage levels, since if the load current is zero the voltage across the load is zero as well. This sudden voltage drop would be seen by other loads as well, if the inductance between two loads is much lower compared to the inductance between the loads and the output capacitors of the power supply. This is only temporary; the inductor ultimately saturates (that is the magnetic field around the conductor reaches its max), the voltage drop across the inductor reaches zero, and the supply voltage comes back to normal. But even a temporary reduction in voltage can disturb adjacent subcircuits. Decoupling caps provide instantenous current jolt which helps maintain constant voltage across a subcircuit (or provide a low impedence path for the transient currents; the description depends on the industry you are in).

To decouple other subcircuits from the effect of the sudden current demand, a decoupling capacitor can be placed between the supply voltage line and its reference (ground) next to the switched load. While the load is switched out, the capacitor charges up to full power supply voltage and otherwise does nothing. When the load is applied, the capacitor initially supplies demanded current. Ideally, by the time the capacitor runs out of charge, the power supply line inductance is saturated, and the load can draw full current at normal voltage from the power supply (and the capacitor can recharge too). Note that the voltage dip is reduced but not eliminated; i.e. the decoupling is not perfect and sometimes parallel combinations of caps are used to improve response. It is worth noting that the best way to reduce switching noise is to design your PCB as a giant capacitor by sendwiching the power and ground planes across a dielectric material.

The size of the capacitor must be reasonable, and there is a tradeoff between capacitor size and signal quality at a given frequency. If a cap is too large it would distort the signal by charging too slowly and filtering out the signal's most needed high-frequency components.

Transient load decoupling

Transient load decoupling as described above is needed when there is a large load that gets switched quickly. The parasitic inductance in every (decoupling) capacitor may limit the suitable capacity and influence appropriate type if switching occurs very fast.

Logic circuits tend to do sudden switching (an ideal logic circuit would switch from low voltage to high voltage instantaneously, with no middle voltage ever observable). So logic circuit boards often have a decoupling capacitor close to each logic IC connected from each power supply connection to a nearby ground. These capacitors decouple every IC from every other IC in terms of supply voltage dips.

These capacitors are often placed at each power source as well as at each analog component in order to ensure that the supplies are as steady as possible. Otherwise, an analog component with poor power supply rejection ratio (PSRR) will copy fluctuations in the power supply onto its output.

In these applications, the decoupling capacitors are often called *bypass capacitors* to indicate that they provide an alternate path for high-frequency signals that would otherwise cause the normally steady supplies to move. Those components that require quick injections of current can *bypass* the power supply by receiving the current from the nearby capacitor. Hence, the slower power supply connection is used to charge these capacitors, and the capacitors actually provide the large quantities of high-availability current.

Placement

A transient load decoupling capacitor should usually be placed as close as possible to the device requiring the decoupled signal. The goal is to minimize the amount of line inductance and series resistance between the decoupling capacitor and that device, and the longer the conductor between the capacitor and the device, the more inductance there is.

A power supply decoupling bypass capacitor should be placed as close to the voltage/current source as possible. The idea is to minimize the line inductance and series resistance between the capacitor and the supplied devices.

The guidelines for placing a high-speed decoupling capacitor on a multi-layer printed circuit board depend on whether the board has dedicated power distribution planes and how closely spaced those planes are.

Since capacitors differ in their high-frequency characteristics (and capacitors with good high-frequency properties are often types with small capacity, while large capacitors usually have worse high-frequency response), decoupling often involves the use of a *combination* of capacitors. For example in logic circuits, a common arrangement is ~100 nF ceramic per logic IC (multiple ones for complex IC's), combined with electrolytic or tantalum capacitor(s) up to a few hundred μF per board / board section.

Noise filters and snubbers

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.

Motor capacitor

A **motor capacitor**, such as a **start capacitor** or **run capacitor**, including a **dual run capacitor**, is an electrical capacitor that alters the current to one or more windings of an electric motor to create a rotating magnetic field. It is used in air conditioners, hot tub/jacuzzi spa pumps, or forced air heat furnaces. A round dual run capacitor (*described below*) is used in some air conditioner compressor units, to boost both the fan and compressor motors.

Motor capacitors include two common types, *run capacitors* and *start capacitors*:

Run capacitors

Run capacitors are designed for continuous duty, and they are energized the entire time the motor is running. Run capacitors are rated in a range of 3–70 microfarads (μF), with voltage classifications of 370 V or 440 V. Single phase electric motors need a capacitor to energize a second-phase winding. If the wrong run capacitor is installed, the motor will not have an even magnetic field, and this will cause the rotor to hesitate at those spots that are uneven. This hesitation can cause the motor to become noisy, increase energy consumption, cause performance to drop, and cause the motor to overheat.

Start capacitors

Start capacitors briefly increase motor starting torque and allow a motor to be cycled on and off rapidly. Start capacitors have ratings above 70 microfarads (μF), with three major voltage classifications: 125 V, 250 V, and 330 V. A start capacitor stays energized long enough to rapidly bring the motor to 3/4 of full speed and is then taken out of the circuit, such as by a centrifugal switch that releases when rotating at or around that speed.

Examples of motor capacitors are: a 35 μF, at 370 V, run capacitor, or an 88–108 μF at 250 V start capacitor.

Dual run capacitors

A dual run capacitor supports 2 electric motors, such as in large air conditioner or heat pump units, with both a fan motor and a compressor motor. The dual capacitor has 3 terminals labeled "C", "FAN", and "HERM" for the common, fan, and hermetic compressor connections.

Round dual run capacitors (shaped as round cylinders) are commonly used for air conditioning, to help in the starting of the compressor and the condenser fan motor. Dual capacitors come in a variety of sizes, depending on microfarads (μF), such as 40 plus 5 μF, and also the voltage. A 440 volt capacitor can be used in place of a 370 volt, but not a 370 in place of a 440 volt. The microfarads must stay the same within 5% of its original value. An oval dual run capacitor could be used instead of a round capacitor, but the mounting strap should be changed to better fit the oval shape.

A faulty dual capacitor often becomes swollen up, with the sides or ends bowed or bulged out further than usual: it can be clear to see that the capacitor has failed because it is swollen or even blown apart with capacitor oil leaking. The U.S. EPA stopped allowing manufacturers to produce capacitors with cancer causing PCBs, and because of the replacement materials, the capacitors now have a limited shelf life. When a dual capacitor fails in an A/C compressor unit, either the outdoor fan does not run, the compressor does not run, or both the fan and the compressor motors do not run.

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.

Sensing

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

Changing the dielectric:
The effects of varying the physical and/or electrical characteristics of the **dielectric** can also be of use. 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 diagphragms, 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, e.g. as 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 his 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.

Chapter- 4

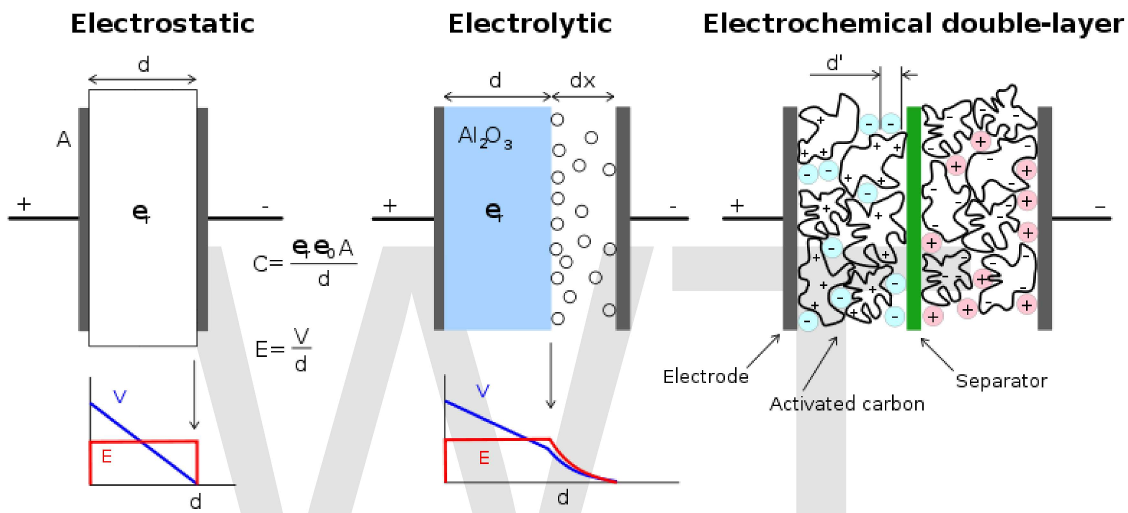
Electric Double-layer Capacitor

Maxwell Technologies "MC" and "BC" series supercapacitors (up to 3000 farad capacitance)

An **electric double-layer capacitor**, also known as **supercapacitor**, **supercondenser**, **pseudocapacitor**, **electrochemical double layer capacitor** (**EDLC**), or **ultracapacitor**, is an electrochemical capacitor that has an unusually high energy density when compared to common capacitors, typically on the order of thousands of times greater than a high capacity electrolytic capacitor. For instance, a typical D-cell sized electrolytic capacitor will have a capacitance in the range of tens of millifarads. The same size electric double-layer capacitor would have a capacitance of several farads, an improvement of about two or three orders of magnitude in capacitance, but usually at a lower working voltage. Larger double-layer capacitors have capacities up to 5,000 farads as of 2010. The highest energy density in production is 30 Wh/kg, below rapid-charging Lithium-titanate batteries.

EDLCs have a variety of commercial applications, notably in "energy smoothing" and momentary-load devices. They have applications as energy-storage devices used in vehicles, and for smaller applications like home solar energy systems where extremely fast charging is a valuable feature.

Concept



Comparison of construction diagrams of three capacitors. Left: "normal" capacitor, middle: electrolytic, right: electric double-layer capacitor

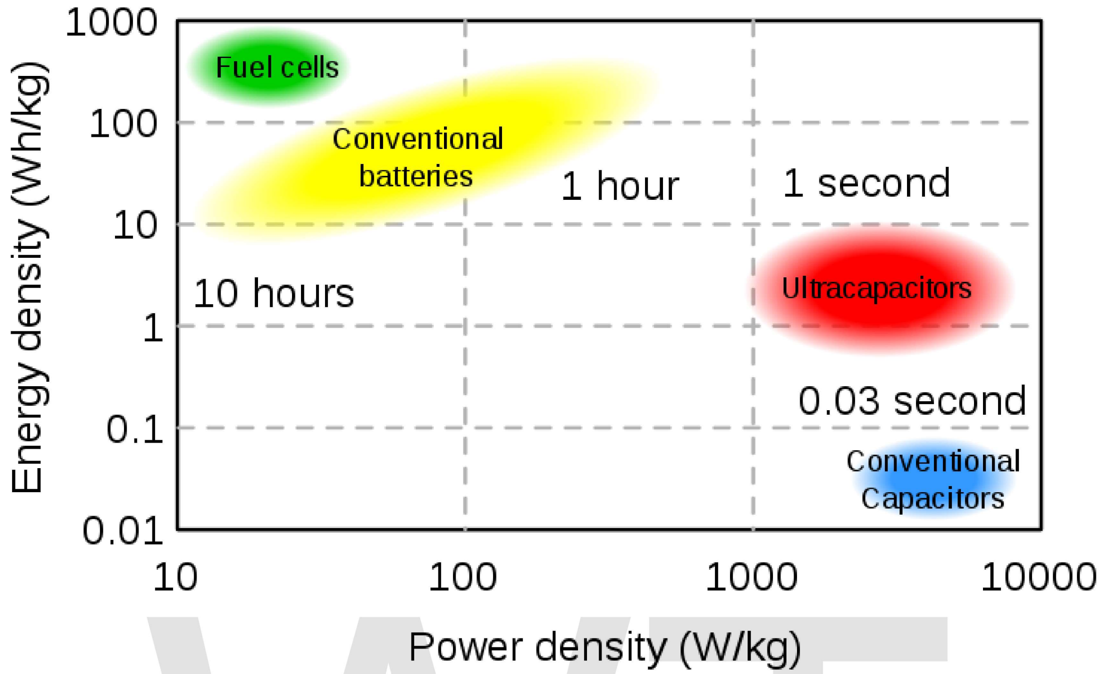
In a conventional capacitor, energy is stored by the removal of charge carriers, typically electrons, from one metal plate and depositing them on another. This charge separation creates a potential between the two plates, which can be harnessed in an external circuit. The total energy stored in this fashion is proportional to both the amount of charge stored and the potential between the plates. The amount of charge stored per unit voltage is essentially a function of the size, the distance, and the material properties of the plates and the dielectric (i.e. the material in between the plates), while the potential between the plates is limited by dielectric breakdown of the substance separating the plates. Different materials sandwiched between the plates to separate them result in different voltages to be stored. Optimizing the material leads to higher energy densities for any given size of capacitor.

EDLCs do not have a conventional dielectric. Rather than two separate plates separated by an intervening substance, these capacitors use "plates" that are in fact two layers of the same substrate, and their electrical properties, the so-called "electrical double layer", result in the effective separation of charge despite the vanishingly thin (on the order of nanometers) physical separation of the layers. The lack of need for a bulky layer of dielectric permits the packing of "plates" with much larger surface area into a given size, resulting in extraordinarily high capacitances in practical-sized packages.

In an electrical double layer, each layer by itself is quite conductive, but the physics at the interface where the layers are effectively in contact means that no significant current can flow between the layers. However, the double layer can withstand only a low voltage, which means that electric double-layer capacitors rated for higher voltages must be made of matched series-connected individual EDLCs, much like series-connected cells in higher-voltage batteries.

In general, EDLCs improve storage density through the use of a nanoporous material, typically activated charcoal, in place of the conventional insulating barrier. Activated charcoal is a powder made up of extremely small and very "rough" particles, which, in bulk, form a low-density volume of particles with holes between them that resembles a sponge. The overall surface area of even a thin layer of such a material is many times greater than a traditional material like aluminum, allowing many more charge carriers (ions or radicals from the electrolyte) to be stored in any given volume. The charcoal, which is not a good insulator, is taking the place of the excellent insulators used in conventional devices, so in general EDLCs can only use low potentials on the order of 2 to 3 V.

Activated charcoal is not the "perfect" material for this application. The charge carriers are actually (in effect) quite large—especially when surrounded by solvent molecules—and are often larger than the holes left in the charcoal, which are too small to accept them, limiting the storage. Most recent research in EDLCs has focused on improved materials that offer even higher *usable* surface areas. Experimental devices developed at MIT replace the charcoal with carbon nanotubes, which can store about the same charge as charcoal (which is almost pure carbon) but are mechanically arranged in a much more regular pattern that exposes a much greater suitable surface area. Other teams are experimenting with custom materials made of activated polypyrrole, and nanotube-impregnated papers.



Ragone chart showing energy density vs. power density for various energy-storage devices

The energy density of existing commercial EDLCs ranges from around 0.5 to 30 W·h/kg, with the standardized cells available from Maxwell Technologies rated at 6 W·h/kg and ACT in production of 30 W·h/kg.

ACT's capacitor is actually a lithium ion capacitor, known also as a "hybrid capacitor". Experimental electric double-layer capacitors from the MIT LEES project have demonstrated densities of 30 W·h/kg and appear to be scalable to 60 W·h/kg in the short term, while EEStor claims their examples will offer energy densities of about 400 W·h/kg. For comparison, a conventional lead-acid battery stores typically 30 to 40 W·h/kg and modern lithium-ion batteries about 160 W·h/kg. Gasoline has a net calorific value (NCV) of around 12,000 W·h/kg; automobile applications operate at about 20% tank-to-wheel efficiency, giving an effective energy density of 2,400 W·h/kg.

EDLCs have much higher power density than batteries. Power density combines the energy density with the speed that the energy can be delivered to the load. Batteries, which are based on the movement of charge carriers in a liquid electrolyte, have relatively slow charge and discharge times. Capacitors, on the other hand, can be charged or discharged at a rate that is typically limited by current heating of the electrodes. So while existing EDLCs have *energy* densities that are perhaps 1/10th that of a conventional battery, their *power* density is generally 10 to 100 times as great.

History

The EDLC effect was first noticed in 1957 by General Electric engineers experimenting with devices using porous carbon electrodes. It was believed that the energy was stored in the carbon pores and it exhibited "exceptionally high capacitance", although the mechanism was unknown at that time.

General Electric did not immediately follow up on this work, and the modern version of the devices was eventually developed by researchers at Standard Oil of Ohio in 1966, after they accidentally re-discovered the effect while working on experimental fuel cell designs. Their cell design used two layers of activated charcoal separated by a thin porous insulator, and this basic mechanical design remains the basis of most electric double-layer capacitors to this day.

Standard Oil also failed to commercialize their invention, licensing the technology to NEC, who finally marketed the results as "supercapacitors" in 1978, to provide backup power for maintaining computer memory. The market expanded slowly for a time, but starting around the mid-1990s various advances in materials science and simple development of the existing systems led to rapidly improving performance and an equally rapid reduction in cost.

The first trials of supercapacitors in industrial applications were carried out for supporting the energy supply to robots.

In 2005 aerospace systems and controls company Diehl Luftfahrt Elektronik GmbH chose ultracapacitors Boostcap (of Maxwell Technologies) to power emergency actuation systems for doors and evacuation slides in airliners, including the new Airbus 380 jumbo jet. Also in 2005, the ultracapacitor market was between US $272 million and $400 million, depending on the source.

In 2006 Joel Schindall and his team at MIT began working on a "super battery", using nanotube technology to improve upon capacitors. They hope to put them on the market within five years.

In 2007 all solid state micrometer-scale electric double-layer capacitors based on advanced superionic conductors have been for future low-voltage electronics such as deep-sub-voltage nanoelectronics and related technologies (the 22 nm technological node of CMOS and beyond).

Technology

Supercapacitors have several disadvantages and advantages relative to batteries, as described below.

Disadvantages

- The amount of energy stored per unit weight is considerably lower than that of an electrochemical battery (3–5 W·h/kg for an ultracapacitor as of 2010 compared to

30-40 W·h/kg for a lead acid battery), and about 1/1,000th the volumetric energy density of gasoline.

- As with any capacitor, the voltage varies with the energy stored. Effective storage and recovery of energy requires complex electronic control and switching equipment, with consequent energy loss
- Has the highest dielectric absorption of any type of capacitor.
- High self-discharge - the rate is considerably higher than that of an electrochemical battery.
- Cells have low voltages - serial connections are needed to obtain higher voltages. Voltage balancing is required if more than three capacitors are connected in series.
- Linear discharge voltage prevents use of the full energy spectrum.
- Due to rapid and large release of energy (albeit over short times), EDLC's have the potential to be deadly to humans. One example is the case of rescue workers accidentally discharging an ultracap in hybrid electrics during automobile accidents.

Advantages

- Long life, with little degradation over hundreds of thousands of charge cycles. Due to the capacitor's high number of charge-discharge cycles (millions or more compared to 200 to 1000 for most commercially available rechargeable batteries) it will last for the entire lifetime of most devices, which makes the device environmentally friendly. Rechargeable batteries wear out typically over a few years, and their highly reactive chemical electrolytes present a disposal and safety hazard. Battery lifetime can be optimised by only charging under favorable conditions, at an ideal rate and, for some chemistries, as infrequently as possible. EDLCs can help in conjunction with batteries by acting as a charge conditioner, storing energy from other sources for load balancing purposes and then using any excess energy to charge the batteries at a suitable time.
- Low cost *per cycle*
- Good reversibility
- Very high rates of charge and discharge.
- Extremely low internal resistance (ESR) and consequent high cycle efficiency (95% or more) and extremely low heating levels
- High output power
- High specific power. According to ITS (Institute of Transportation Studies, Davis, California) test results, the specific power of electric double-layer capacitors can exceed 6 kW/kg at 95% efficiency
- Improved safety, no corrosive electrolyte and low toxicity of materials.
- Rapid charging—supercapacitors charge in seconds.
- Simple charge methods—no full-charge detection is needed; no danger of overcharging.

Materials

Activated carbon, graphene, carbon nanotubes and certain conductive polymers, or carbon aerogels, are practical for supercapacitors:

Virtually all commercial supercapacitors manufactured by Panasonic, Nesscap, Maxwell Technologies, Nippon Chemi-Con, Axion Power, and others use powdered activated carbon made from coconut shells. Some companies also build higher performance devices, at a significant cost increase, based on synthetic carbon precursors that are activated with potassium hydroxide (KOH).

- Graphene has excellent surface area per unit of gravimetric or volumetric densities, is highly conductive and can now be produced in various labs. It will not be long before large volumes of Graphene are produced for use in supercapacitors.

- Carbon nanotubes have excellent nanoporosity properties, allowing tiny spaces for the polymer to sit in the tube and act as a dielectric. MIT's Laboratory of Electromagnetic and Electronic Systems (LEES) is researching using carbon nanotubes.

- Some polymers (eg. polyacenes) have a redox (reduction-oxidation) storage mechanism along with a high surface area.

- Supercapacitors are also being made of carbon aerogel. This is a unique material providing extremely high surface area of about 400-1000 m^2/g. The electrodes of aerogel supercapacitors are usually made of non-woven paper made from carbon fibers and coated with organic aerogel, which then undergoes pyrolysis. The paper is a composite material where the carbon fibers provide structural integrity and the aerogel provides the required large surface. Small aerogel supercapacitors are being used as backup electricity storage in microelectronics, but applications for electric vehicles are expected. Aerogel capacitors can only work at a few volts; higher voltages would ionize the carbon and damage the capacitor. Carbon aerogel capacitors have achieved 325 J/g (90 W·h/kg) energy density and 20 W/g power density.

- The company Reticle claims to be able to make supercapacitors from solid activated carbon, which they call *consolidated amorphous carbon* (CAC). It can have a surface area exceeding 2800 m^2/g and according to US patent 6787235 may be cheaper to produce than aerogel carbon.

- Systematic pore size control and H_2 adsorption treatment showed by Y-Carbon to produce tunable nanoporous carbon can be used to increase the energy density by as much as 75% over what is commercially available as of 2005.

- The company Tartu Technologies developed supercapacitors from mineral-based carbon. This nonactivated carbon is synthesised from metal or metalloid carbides, e.g. SiC, TiC, Al4C3, etc. as claimed in US patent 6602742 and WO patent 2005118471. The synthesised nanostructured porous carbon, often called Carbide Derived Carbon (CDC), has a surface area of about 400 m²/g to 2000 m²/g with a specific capacitance of up to 100 F/mL (in organic electrolyte). As of 2006 they claimed a supercapacitor with a volume of 135 mL and 200 g weight having 1.6 kF capacitance. The energy density is more than 47 kJ/L at 2.85 V and power density of over 20 W/g.

- In August 2007 a research team at RPI developed a paper battery with aligned carbon nanotubes, designed to function as both a lithium-ion battery and a supercapacitor (called *bacitor*), using an ionic liquid, essentially a liquid salt, as the electrolyte. The sheets can be rolled, twisted, folded, or cut into numerous shapes with no loss of integrity or efficiency, or stacked, like printer paper (or a voltaic pile), to boost total output. Further, they can be made in a variety of sizes, from postage stamp to broadsheet. Their light weight and low cost make them attractive for portable electronics, aircraft, automobiles, and toys (such as model aircraft), while their ability to use electrolytes in blood make them potentially useful for medical devices such as pacemakers. They are biodegradable.

Applications

Vehicles

Heavy and public transport

Some of the earliest uses were motor startup capacitors for large engines in tanks and submarines, and as the cost has fallen they have started to appear on diesel trucks and railroad locomotives. More recently they have become a topic of some interest in the green energy world, where their ability to store energy much faster than batteries makes them particularly suitable for regenerative braking applications. New technology in development could potentially make EDLCs with high enough energy density to be an attractive replacement for batteries in all-electric cars and plug-in hybrids, as EDLCs charge quickly and are stable with temperature.

China is experimenting with a new form of electric bus (capabus) that runs without powerlines using power stored in large onboard EDLCs, which are quickly recharged whenever the bus is at any bus stop (under so-called **electric umbrellas**), and fully charged in the terminus. A few prototypes were being tested in Shanghai in early 2005. In 2006, two commercial bus routes began to use electric double-layer capacitor buses; one of them is route 11 in Shanghai.

In 2001 and 2002 VAG, the public transport operator in Nuremberg, Germany tested an hybrid bus that uses a diesel-electric battery drive system with electric double-layer capacitors.

Since 2003 Mannheim Stadtbahn in Mannheim, Germany has operated an LRV (light-rail vehicle) that uses electric double-layer capacitors to store braking energy.

Other companies from the public transport manufacturing sector are developing electric double-layer capacitor technology: The Transportation Systems division of Siemens AG is developing a mobile energy storage based on double-layer capacitors called Sibac Energy Storage and also Sitras SES, a stationary version integrated into the trackside power supply. The company Cegelec is also developing an electric double-layer capacitor-based energy storage system.

Proton Power Systems has created the world's first triple hybrid Forklift Truck, which uses fuel cells and batteries as primary energy storage and EDLCs to supplement this energy storage solution.

Private vehicles

Ultracapacitors are used in some electric vehicles, such as AFS Trinity's concept prototype, to store rapidly available energy with their high power density, in order to keep batteries within safe resistive heating limits and extend battery life. The ultrabattery combines a supercapacitor and a battery in one unit, creating an electric vehicle battery that lasts longer, costs less and is more powerful than current technologies used in plug-in hybrid electric vehicles (PHEVs).

Motor racing

The FIA, the governing body for many motor racing events, proposed in the *Power-Train Regulation Framework for Formula 1* version 1.3 of 23 May 2007 that a new set of power train regulations be issued that includes a hybrid drive of up to 200 kW input and output power using "superbatteries" made with both batteries and supercapacitors.

Consumer electronics

EDLCs can be used in PC Cards, flash photography devices in digital cameras, flashlights, portable media players, and in automated meter reading, particularly where extremely fast charging is desirable.

In 2007, a cordless electric screwdriver that uses an EDLC for energy storage was produced. It charges in 90 seconds, retains 85% of the charge after 3 months, and holds enough charge for about half the screws (22) a comparable screwdriver with a rechargeable battery will handle (37). Two LED flashlights using EDLCs were released in 2009. They charge in 90 seconds

Alternative energy sources

The idea of replacing batteries with capacitors in conjunction with novel alternative energy sources became a conceptual umbrella of the Green Electricity (GEL) Initiative, introduced by Dr. Alexander Bell. One particular successful implementation of the GEL Initiative concept was a muscle-driven autonomous solution that employs a multi-farad EDLC (hecto- and kilofarad range capacitors are now available) as an intermediate energy storage to power a variety of portable electrical and electronic devices such as MP3 players, AM/FM radios, flashlights, cell phones, and emergency kits. As the energy density of EDLCs is bridging the gap with batteries, the vehicle industry is deploying ultracapacitors as a replacement for chemical batteries.

Several companies have begun capitalizing on this maturing technology, which can provide significant power and energy from a small component. Companies that have been conducting research and technology for this emerging industry are listed below:

- CAP-XX Ltd
- EnerG2
- Fluidic Energy Inc.
- Graphene Energy Inc.
- Maxwell Technologies
- Ioxus, Inc.

Price

Costs have fallen quickly, with cost per kilojoule dropping faster than cost per farad. As of 2006 the cost of supercapacitors was 1 cent per farad and $2.85 per kilojoule, and was expected to drop further.

Market

According to Innovative Research and Products (iRAP), ultracapacitor market growth will continue during 2009 to 2014. Worldwide business, over US$275 million in 2009, will continue to grow at an AAGR of 21.4% through 2014.

Chapter- 5

Capacitance

In electromagnetism and electronics, **capacitance** is the ability of a body to hold an electrical charge. Capacitance is also a measure of the amount of electrical energy stored (or separated) for a given electric potential. A common form of energy storage device is a parallel-plate capacitor. In a parallel plate capacitor, capacitance is directly proportional to the surface area of the conductor plates and inversely proportional to the separation distance between the plates. If the charges on the plates are $+Q$ and $-Q$, and V gives the voltage between the plates, then the capacitance is given by

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

The SI unit of capacitance is the farad; 1 farad is 1 coulomb per volt.

The energy (measured in joules) stored in a capacitor is equal to the *work* done to charge it. Consider a capacitance C, holding a charge $+q$ on one plate and $-q$ on the other. Moving a small element of charge dq from one plate to the other against the potential difference $V = q/C$ requires the work dW:

$$\mathrm{d}W = \frac{q}{C}\,\mathrm{d}q$$

where W is the work measured in joules, q is the charge measured in coulombs and C is the capacitance, measured in farads.

The energy stored in a capacitance is found by integrating this equation. Starting with an uncharged capacitance ($q = 0$) and moving charge from one plate to the other until the plates have charge $+Q$ and $-Q$ requires the work W:

$$W_{\text{charging}} = \int_0^Q \frac{q}{C}\,\mathrm{d}q = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}CV^2 = W_{\text{stored}}.$$

Capacitors

The capacitance of the majority of capacitors used in electronic circuits is several orders of magnitude smaller than the farad. The most common subunits of capacitance in use today are the millifarad (mF), microfarad (µF), nanofarad (nF) and picofarad (pF).

The capacitance can be calculated if the geometry of the conductors and the dielectric properties of the insulator between the conductors are known. For example, the capacitance of a *parallel-plate* capacitor constructed of two parallel plates both of area *A* separated by a distance *d* is approximately equal to the following:

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

where

C is the capacitance;
A is the area of overlap of the two plates;
ε_r is the relative static permittivity (sometimes called the dielectric constant) of the material between the plates (for a vacuum, $\varepsilon_r = 1$);
ε_0 is the electric constant ($\varepsilon_0 \approx 8.854\times10^{-12}$ F m^{-1}); and
d is the separation between the plates.

Capacitance is proportional to the area of overlap and inversely proportional to the separation between conducting sheets. The closer the sheets are to each other, the greater the capacitance. The equation is a good approximation if *d* is small compared to the other dimensions of the plates so the field in the capacitor over most of its area is uniform, and the so-called *fringing field* around the periphery provides a small contribution. In CGS units the equation has the form:

$$C = \varepsilon_r \frac{A}{4\pi d}$$

where *C* in this case has the units of length.

Combining the SI equation for capacitance with the above equation for the energy stored in a capacitance, for a flat-plate capacitor the energy stored is:

$$W_{stored} = \frac{1}{2}CV^2 = \frac{1}{2}\varepsilon_r \varepsilon_0 \frac{A}{d} V^2.$$

where *W* is the energy, in joules; *C* is the capacitance, in farads; and *V* is the voltage, in volts.

Voltage dependent capacitors

The dielectric constant for a number of very useful dielectrics changes as a function of the applied electrical field, for example ferroelectric materials, so the capacitance for these devices is more complex. For example, in charging such a capacitor the differential increase in voltage with charge is governed by:

$$dQ = C(V)\,dV\ ,$$

where the voltage dependence of capacitance, $C(V)$, stems from the field, which in a large area parallel plate device is given by $\varepsilon = V/d$. This field polarizes the dielectric, which polarization, in the case of a ferroelectric, is a nonlinear S-shaped function of field, which, in the case of a large area parallel plate device, translates into a capacitance that is a nonlinear function of the voltage causing the field.

Corresponding to the voltage-dependent capacitance, to charge the capacitor to voltage V an integral relation is found:

$$Q = \int_0^V dV\ C(V)\ ,$$

which agrees with $Q = CV$ only when C is voltage independent.

By the same token, the energy stored in the capacitor now is given by

$$dW = QdV = \left[\int_0^V\ dV'\ C(V')\right]\ dV\ .$$

Integrating:

$$W = \int_0^V\ dV\ \int_0^V\ dV'\ C(V') = \int_0^V\ dV'\ \int_{V'}^V\ dV\ C(V')$$
$$= \int_0^V\ dV'\,(V - V')\,C(V')\ ,$$

where interchange of the order of integration is used.

The nonlinear capacitance of a microscope probe scanned along a ferroelectric surface is used to study the domain structure of ferroelectric materials.

Another example of voltage dependent capacitance occurs in semiconductor devices such as semiconductor diodes, where the voltage dependence stems not from a change in dielectric constant but in a voltage dependence of the spacing between the charges on the two sides of the capacitor.

Frequency dependent capacitors

If a capacitor is driven with a time-varying voltage that changes rapidly enough, then the polarization of the dielectric cannot follow the signal. As an example of the origin of this mechanism, the internal microscopic dipoles contributing to the dielectric constant cannot move instantly, and so as frequency of an applied alternating voltage increases, the dipole response is limited and the dielectric constant diminishes. A changing dielectric constant with frequency is referred to as dielectric dispersion, and is governed by dielectric relaxation processes, such as Debye relaxation. Under transient conditions, the displacement field can be expressed as:

$$\boldsymbol{D}(t) = \varepsilon_0 \int_{-\infty}^{t} dt' \ \varepsilon_r(t-t')\boldsymbol{E}(t') \ ,$$

indicating the lag in response by the time dependence of ε_r, calculated in principle from an underlying microscopic analysis, for example, of the dipole behavior in the dielectric. See, for example, linear response function. The integral extends over the entire past history up to the present time. A Fourier transform in time then results in:

$$\boldsymbol{D}(\omega) = \varepsilon_0 \varepsilon_r(\omega)\boldsymbol{E}(\omega) \ ,$$

where $\varepsilon_r(\omega)$ is now a complex function, with an imaginary part related to absorption of energy from the field by the medium. The capacitance, being proportional to the dielectric constant, also exhibits this frequency behavior. Fourier transforming Gauss's law with this form for displacement field:

$$I(\omega) = j\omega Q(\omega) = j\omega \oint_{\Sigma} \boldsymbol{D}(\boldsymbol{r}, \ \omega) \cdot d\boldsymbol{\Sigma}$$
$$= \left[G(\omega) + j\omega C(\omega)\right] V(\omega) = \frac{V(\omega)}{Z(\omega)} \ ,$$

where j is the imaginary unit, $V(\omega)$ is the voltage component at angular frequency ω, $G(\omega)$ is the *real* part of the current, called the *conductance*, and $C(\omega)$ determines the *imaginary* part of the current and is the *capacitance*. $Z(\omega)$ is the complex impedance.

When a parallel-plate capacitor is filled with a dielectric, the measurement of dielectric properties of the medium is based upon the relation:

$$\varepsilon_r(\omega) = \varepsilon'_r(\omega) - j\varepsilon''_r(\omega) = \frac{1}{j\omega Z(\omega) C_0} = \frac{C(\omega)}{C_0} \ ,$$

where a single *prime* denotes the real part and a double *prime* the imaginary part, $Z(\omega)$ is the complex impedance with the dielectric present, $C(\omega)$ is the so-called *complex* capacitance with the dielectric present, and C_0 is the capacitance without the dielectric.

(Measurement "without the dielectric" in principle means measurement in free space, an unattainable goal inasmuch as even the quantum vacuum is predicted to exhibit nonideal behavior, such as dichroism. For practical purposes, when measurement errors are taken into account, often a measurement in terrestrial vacuum, or simply a calculation of C_0, is sufficiently accurate.)

Using this measurement method, the dielectric constant may exhibit a resonance at certain frequencies corresponding to characteristic response frequencies (excitation energies) of contributors to the dielectric constant. These resonances are the basis for a number of experimental techniques for detecting defects. The *conductance method* measures absorption as a function of frequency. Alternatively, the time response of the capacitance can be used directly, as in *deep-level transient spectroscopy*.

Another example of frequency dependent capacitance occurs with MOS capacitors, where the slow generation of minority carriers means that at high frequencies the capacitance measures only the majority carrier response, while at low frequencies both types of carrier respond.

At optical frequencies, in semiconductors the dielectric constant exhibits structure related to the band structure of the solid. Sophisticated modulation spectroscopy measurement methods based upon modulating the crystal structure by pressure or by other stresses and observing the related changes in absorption or reflection of light have advanced our knowledge of these materials.

Capacitance matrix

The discussion above is limited to the case of two conducting plates, although of arbitrary size and shape. The definition C=Q/V still holds for a single plate given a charge, in which case the field lines produced by that charge terminate as if the plate were at the center of an oppositely charged sphere at infinity.

$C = Q / V$ does not apply when there are more than two charged plates, or when the net charge on the two plates is non-zero. To handle this case, Maxwell introduced his "coefficients of potential". If three plates are given charges Q_1,Q_2,Q_3, then the voltage of plate 1 is given by

$$V_1 = P_{11}Q_1 + P_{12}Q_2 + P_{13}Q_3,$$

and similarly for the other voltages. Maxwell showed that the coefficients of potential are symmetric, so that $P_{12} = P_{21}$, etc. Thus the system can be described by a collection of coefficients known as the "Reciprocal Capacitance Matrix"is used, which is defined as:

$$P_{ij} = \frac{V_i}{Q_j}$$

From this, the mutual capacitance C_m between two objects can be defined by solving for the total charge Q and using $C_m = Q / V$.

$$C_m = \frac{V}{(P_{11} + P_{22}) - (P_{12} + P_{21})}$$

Technically speaking, since no actual device holds perfectly equal and opposite charges on each of the two "plates", it is the mutual capacitance that is reported on capacitors. The collection of coefficients $C_{ij} = Q_i / V_j$ is known as the capacitance matrix and also describes the capacitance of the system.

Self-capacitance

In electrical circuits, the term *capacitance* is usually a shorthand for the *mutual capacitance* between two adjacent conductors, such as the two plates of a capacitor. There also exists a property called *self-capacitance*, which is the amount of electrical charge that must be added to an isolated conductor to raise its *electrical potential* by one volt. The reference point for this potential is a theoretical hollow conducting sphere, of infinite radius, centered on the conductor. Using this method, the self-capacitance of a conducting sphere of radius R is given by:

$$C = 4\pi\varepsilon_0 R$$

Example values of self-capacitance are:

- for the top "plate" of a van de Graaff generator, typically a sphere 20 cm in radius: 20 pF
- the planet Earth: about 709 µF

Elastance

The inverse of capacitance is called elastance. The unit of elastance is the daraf.

Stray capacitance

Any two adjacent conductors can be considered a capacitor, although the capacitance will be small unless the conductors are close together for long. This (often unwanted) effect is termed "stray capacitance". Stray capacitance can allow signals to leak between otherwise isolated circuits (an effect called crosstalk), and it can be a limiting factor for proper functioning of circuits at high frequency.

Stray capacitance is often encountered in amplifier circuits in the form of "feedthrough" capacitance that interconnects the input and output nodes (both defined relative to a common ground). It is often convenient for analytical purposes to replace this capacitance with a combination of one input-to-ground capacitance and one output-to-ground capacitance. (The original configuration — including the input-to-output capacitance — is often referred to as a pi-configuration.) Miller's theorem can be used to effect this replacement. Miller's theorem states that, if the gain ratio of two nodes is 1/K, then an impedance of Z connecting the two nodes can be replaced with a Z/(1-k) impedance between the first node and ground and a KZ/(K-1) impedance between the second node and ground. (Since impedance varies inversely with capacitance, the internode capacitance, C, will be seen to have been replaced by a capacitance of KC from input to ground and a capacitance of (K-1)C/K from output to ground.) When the input-to-output gain is very large, the equivalent input-to-ground impedance is very small while the output-to-ground impedance is essentially equal to the original (input-to-output) impedance.

Capacitance of simple systems

Calculating the capacitance of a system amounts to solving the Laplace equation $\nabla^2\varphi=0$ with a constant potential φ on the surface of the conductors. This is trivial in cases with high symmetry. There is no solution in terms of elementary functions in more complicated cases.

For quasi two-dimensional situations analytic functions may be used to map different geometries to each other.

Capacitance of simple systems

Type	Capacitance	Comment
Parallel-plate capacitor	$\varepsilon A/d$	A: Area d: Distance ε: Permittivity
Coaxial cable	$\frac{2\pi\varepsilon l}{\ln\left(a_2/a_1\right)}$	a_1: Inner radius a_2: Outer radius l: Length
Pair of parallel wires	$\frac{\pi\varepsilon l}{\operatorname{arcosh}\left(\frac{d}{2a}\right)}=\frac{\pi\varepsilon l}{\ln\left(\frac{d}{2a}+\sqrt{\frac{d^2}{4a^2}-1}\right)}$	a: Wire radius d: Distance, d > 2a l: Length of pair
Wire parallel to wall	$\frac{2\pi\varepsilon l}{\operatorname{arcosh}\left(\frac{d}{a}\right)}=\frac{2\pi\varepsilon l}{\ln\left(\frac{d}{a}+\sqrt{\frac{d^2}{a^2}-1}\right)}$	a: Wire radius d: Distance, d > a l: Wire length
Two parallel coplanar strips	$\varepsilon l\frac{K\left(\sqrt{1-k^2}\right)}{K\left(k\right)}$	d: Distance w_1, w_2: Strip width k_i: $d/(2w_i+d)$

		k^2: k_1k_2 K: Elliptic integral l: Length
Concentric spheres	$\frac{4\pi\varepsilon a_1 a_2}{a_2 - a_1}$	a_1: Inner radius a_2: Outer radius
Two spheres, equal radius	$2\pi\varepsilon a \sum_{n=1}^{\infty} \frac{\sinh\left(\ln\left(D+\sqrt{D^2-1}\right)\right)}{\sinh\left(n\ln\left(D+\sqrt{D^2-1}\right)\right)}$ $= 2\pi\varepsilon a \left\{1 + \frac{1}{2D} + \frac{1}{4D^2} + \frac{1}{8D^3} + \frac{1}{8D^4} + \frac{3}{32D^5} + O\left(\frac{1}{D^6}\right)\right\}$ $= 2\pi\varepsilon a \left\{\ln 2 + \gamma - \frac{1}{2}\ln\left(\frac{d}{a} - 2\right) + O\left(\frac{d}{a} - 2\right)\right\}$	a: Radius d: Distance, d > 2a D = d/2a γ: Euler's constant
Sphere in front of wall	$4\pi\varepsilon a \sum_{n=1}^{\infty} \frac{\sinh\left(\ln\left(D+\sqrt{D^2-1}\right)\right)}{\sinh\left(n\ln\left(D+\sqrt{D^2-1}\right)\right)}$	a: Radius d: Distance, d > a D = d/a
Sphere	$4\pi\varepsilon a$	a: Radius
Circular disc	$8\varepsilon a$	a: Radius
Thin straight wire, finite length	$\frac{2\pi\varepsilon l}{\Lambda}\left\{1 + \frac{1}{\Lambda}(1-\ln 2) + \frac{1}{\Lambda^2}\left[1 + (1-\ln 2)^2 - \frac{\pi^2}{12}\right] + O\left(\frac{1}{\Lambda^3}\right)\right\}$	a: Wire radius l: Length

Mutual capacitance

Mutual capacitance is intentional or unintentional capacitance that occurs between two charge-holding objects or conductors, in which the current passing through one passes over into the other. Unlike mutual inductance, mutual capacitance only works along short distances. In transmission lines, when conductors are closely spaced together, the air or material separating them acts as a dielectric, and the conductors act as capacitor plates.

All objects in the universe, conducting or non-conducting, that hold charge with respect to another exhibit capacitance. An object's capacitance increases when another object is brought closer to it. The human body is a great charge-holding object (capacitor) (this biological property is called body capacitance), and sensitive capacitive detectors can be made to function as proximity detectors. The capacitive property of the human body is also helpful in making touch switches, such as those used in touch-activated lamps. The lamp constantly charges and discharges its metal exterior, measuring a change in capacitance.

When mutual capacitance occurs adversely (unintentionally) between transmission lines, this is an example of crosstalk.