Practical Capacitors

There are all sorts of different kinds of capacitors, and usually a wide variety in each class. However, in the very broad assortment, you'll find that most application requirements can be satisfied with just a few select types. They are …

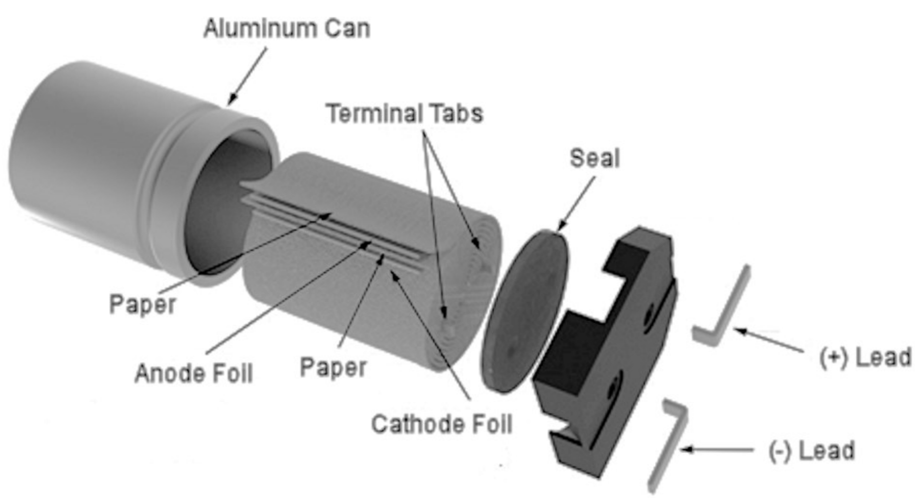
- aluminum electrolytic
- tantalum
- ceramic
- metalized film

There is also no such thing as an "ideal" component in electronics. Practical capacitors, and especially ubiquitous aluminum electrolytics, have limitations that are important to know about.

The Common Capacitor Types

Aluminum electrolytic capacitors are almost always found in electronic equipment because they are used as filter capacitors in the power supplies that convert 120/240vac line power to the low-level DC voltages needed for solid state circuitry. But they can often be found elsewhere in the circuitry also, because they provide large capacitance values at very low cost.

These capacitors consist of two aluminum foils separated by a spacer which is saturated with a conductive liquid or gel-like electrolyte.



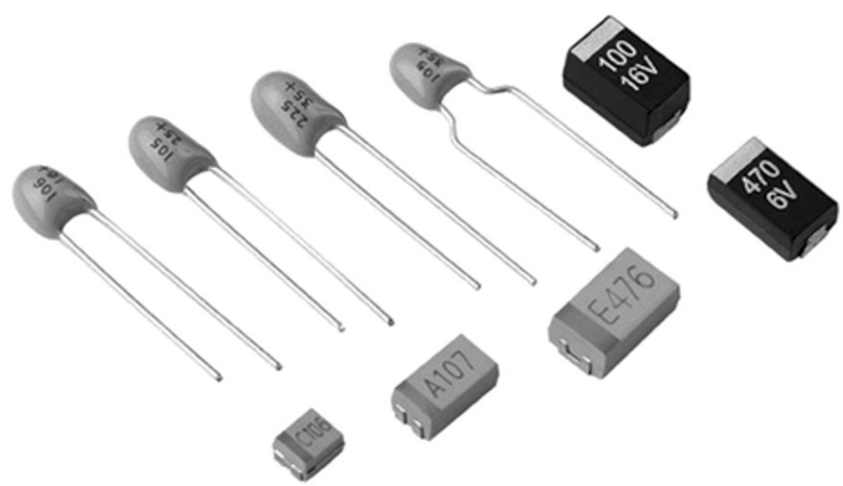
One of the aluminum foils serves as one plate of the capacitor. It is etched to increase its surface area and then oxidized. The oxidation serves as the dielectric. The second aluminum foil serves only to make electrical contact with the electrolyte, which serves as the second plate. After impregnation with electrolyte, the windings are assembled into an aluminum case and sealed.

The very thin oxidation layer is the key to achieving higher capacitance values per unit volume than any other type, and much less expensively. Capacitance values range from

0.1µF to upwards of 3-Farads, with working voltage ratings from 4vdc to 630vdc. Should the integrity of the dielectric layer be compromised by arcing, as a result of transient voltage spikes for example, the electrolyte provides oxygen for re-forming or self-healing of the oxide layer.

Aluminum electrolytic capacitors are polarized. Because of the oxidation scheme, they can only be operated with DC voltage applied with the correct polarity. Operating them with the wrong polarity or with AC voltage usually leads to circuit failure and will probably destroy the capacitor. Such failures are sometimes easily detectable by visual inspection when the capacitor casing is bloated or leaking.

Solid tantalum capacitors are also electrolytic devices. Having very low impedance, they are very useful as bypass capacitors. They are also useful for timing circuits, and other applications that take advantage of their stable electrical characteristics. Their very small size makes them a natural choice for miniaturized devices.



These capacitors are available in sizes ranging from 1.0nF to 100µF, although they are more commonly available in sizes from 0.1µF to 25.0µF, with working voltages between 2vdc and 50vdc.

Their construction is similar to that of the aluminum electrolytic, except that one plate is made of tantalum on which a very thin layer of tantalum oxide is formed. A solid electrolyte serves as the second plate of this capacitor.

Because of the very thin dielectric layer's superior ability to store energy in an electric field, very high values of capacitance per unit volume can be achieved, and with much lower weight. Tantalum capacitors also have the advantage of very low impedance, and very stable electrical characteristics over a broad range of temperatures.

A primary disadvantage is the high cost of tantalum, which makes these capacitors significantly more expensive than other types. Unlike aluminum electrolytics, they are not self-healing. Being polarized, reverse voltage or high ripple currents can damage the dielectric, thereby destroying the capacitor. The damage is often obvious on visual inspection since they are apt to overheat and appear burnt.

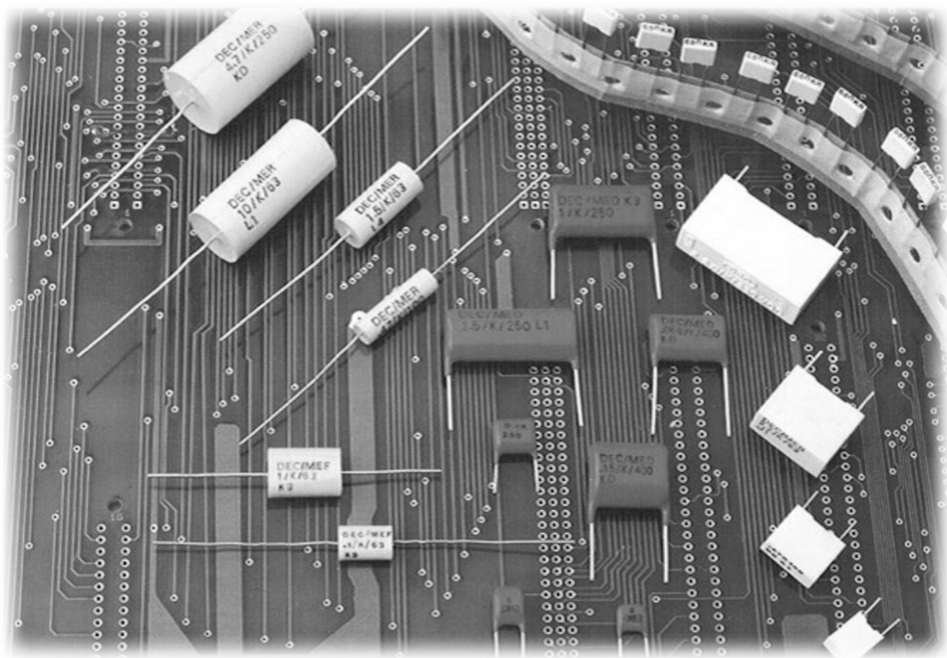
Ceramic capacitors are found in all kinds of circuitry. “Class I” types, featuring low losses and high stability, are especially suitable for precision applications such as tuned circuits and timing. “Class II” capacitors, which have a high dielectric constant and therefore offer high capacitance values in small packages, are chosen for coupling, decoupling and bypass use.

These capacitors are typically available in values ranging from 1.0pF to .022μF, with working voltages from 50vdc to 250vdc. With over one-trillion pieces being shipped by manufacturers each year, ceramic capacitors outnumber any other kind in common use.

They are usually made by fusing layers of ceramic and metal in two or more layers, the ceramic acting as the dielectric. The composition of the ceramic determines the characteristics of the component.

Ceramic capacitors are the most reliable of all capacitor types. Failures that do occur are more often the result of shoddy quality, rather than normal use or aging. The failure mode is usually grossly compromised leakage resistance which impairs or prevents normal circuit functioning, defective capacitors otherwise seldom showing any outwardly visible signs of failure.

<u>Metalized Film capacitors</u> are usually chosen for precision circuits, since they typically feature very low leakage characteristics. They're commonly available in sizes ranging from 100pf to 4.0µF, with working voltages from 50vdc to 750vdc.

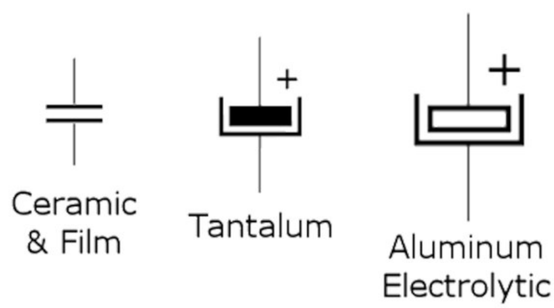


These capacitors use very thin plastic films as their dielectric — typically Mylar, polyester, or polypropylene. In some cases separate aluminum foils are used, but "metalized film" types — a thin layer of aluminum or zinc being deposited directly on the surface of the plastic film — are more common.

Metallized film capacitors have a very interesting "self-healing" property. Arcing may cause momentary point-defect short circuits between the metal electrodes, but the high temperature of the arc vaporizes both the dielectric plastic material at the breakdown point and the metallization around it, thus healing the breach. At the same instant, the resulting vapor pressure also extinguishes the arc. The whole process typically takes less than 10μs, and often completes without interrupting the useful operation of the capacitor. This unique property makes it possible for manufacturers to offer very high quality, supposedly "zero-defect" capacitors.

Schematic Symbols

Symbols used to represent capacitors on schematic diagrams vary. I use what are loosely “European style” symbols. I prefer them because they give some indication of capacitor type, and they are very easy to draw, both manually and when using a CAD system.



Dielectric Constant

The terms “dielectric” and “insulator” are essentially interchangeable; they mean the same thing, referring to a material that does not conduct electric current.

But such materials do not necessarily block electric fields. The extent to which they are able to resist the formation of an electric field within themselves is called *permittivity*, or more generally in the case of capacitors, their *dielectric constant*.

In a capacitor, capacitance depends on the size of the plates, the amount of space between the plates, and the strength of the field between the plates — which is determined by the dielectric constant of the material between them.

So what's going on within the dielectric material?

Without getting too involved since an understanding of this isn't really essential — the electric field in the dielectric material is developed by the distortion, or "stretching", of the electron orbits, and polar realignment of electron spins. The dielectric constant is a number representing how permissive a material is to these sorts of changes. A higher number reflects increased permittivity, and therefore greater flux density in the field. All other factors being equal, that produces higher levels of capacitance.

The dielectric constant for some typically-used materials are …

- air = 1
- teflon = 2
- plastics= 2 to 3.5
- mica = 6
- aluminum oxide = 7
- tantalum = 27
- ceramics = 35 to over 6,000

Leakage, Equivalent Series Resistance, and Breakdown Voltage

From the above, one might easily jump to the conclusion that in making a capacitor, insulating materials with a very high dielectric constant would always be the best choice.

That, of course, is not necessarily so.

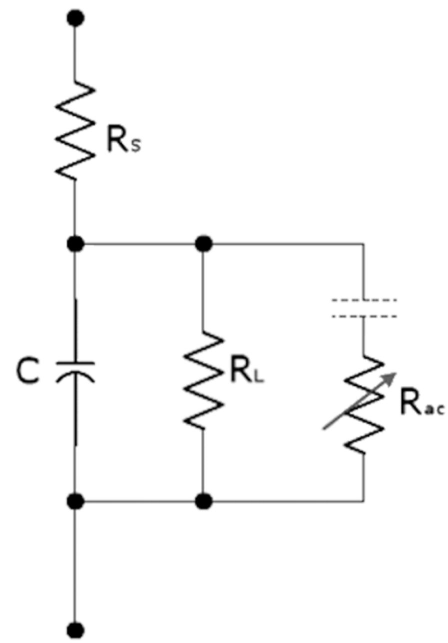
Every insulator can be forced to conduct current if the voltage is high enough; a situation that is called *dielectric breakdown*. Materials with a high dielectric constant do not necessarily have a high dielectric breakdown characteristic. For a given working voltage, their use would therefore require increasing the distance between the plates. That would result in decreased capacitance, thus defeating the purpose of choosing that particular material.

Materials that have both a high dielectric constant and a high dielectric breakdown characteristic are also generally costlier, either for the material itself, or the more complicated manufacturing process. The choice of such materials would therefore be appropriate only for capacitors being designed for some special purpose.

So the choice of dielectrics is a trade-off among several such factors.

Imperfections in practical capacitors include …

- actual series resistance (R_S)
- leakage resistance (R_L)
- dielectric loss (Rac)



R_S is the DC resistance of the leads and foil. It appears to be in series with the capacitor, is always very low, and is usually negligible.

R_L is the leakage resistance, representing DC leakage current through the dielectric. It acts like a very high parallel resistance. In capacitors with plastic dielectrics such as polyethylene or polypropylene, it can be 10GΩ or more, and therefore negligible. In

other kinds of capacitors, the leakage current can be much higher, limiting their usefulness for certain functions.

R_{ac} represents a dielectric loss which varies with frequency. The "ac" represents 'alternating current' — the capacitor in this leg signifying that this path is blocked for DC current.

The term *equivalent series resistance* (*ESR*) is somewhat of a misnomer, since it includes all three of these losses. With the exception of precision timing circuits, it becomes significant more often with respect to failure modes, than to normal circuit design considerations.

With respect to reliability, the significance of ESR is its resistive nature. Recall that current through a resistance results in an I^2R power loss, the lost energy usually being dissipated in the form of heat.

Ceramic capacitors typically have a very low ESR, between 0.01 and 0.1 ohms. This is typical for non-electrolytic capacitors, and the ESR tends to remain quite stable over time. For all practical purposes non-electrolytic capacitors can be treated as ideal components.

Aluminum electrolytic capacitors have much higher ESR values — up to several ohms. Their ESR tends to increase with frequency, and also over time as the capacitor ages. High ambient temperatures and large ripple currents exacerbate the problem. The ESR can increase enough to ultimately cause circuit malfunctions and even permanent damage to the capacitor as a result of I^2R heating, even though the measured capacitance may remain within tolerance.

Since ESR can only be measured with highly a specialized instrument, unless damage to the capacitor is obvious on visual inspection, these problems can be difficult to diagnose. The only practical troubleshooting alternative is to replace suspect capacitors with new ones.

As a real-life example, the power supply for many flat-panel computer displays, including Dell's, are more or less all the same, with a circuit board including about fourteen aluminum electrolytic capacitors. When these monitors go black after a time, the fix is to remove and replace all the capacitors on that circuit board. The failure is so typical that capacitor kits including the fourteen values needed are commonly offered on Amazon.com, eBay, and elsewhere.

On the other hand, in the products we manufactured over the past 40-years, I can recall very few, if any, such failures. So the message is that there's a difference between using quality components, and using the cheapest ones that money can buy.

In the next installment, we are going to have a look at some simple circuits containing both types of reactive components — inductors and capacitors — and we'll see how they respond to alternating signals.

Do you already know something about *trigonometric functions* and *vector analysis*?

No?

Well, good! Tomorrow will be your lucky day!
