Electrolytic capacitor

Cardboard enclosed axial lead electrolytic capacitors in a 1930s tube radio

Axial lead (top) and radial lead (bottom) electrolytic capacitors

An **electrolytic capacitor** is a type of capacitor that uses an ionic conducting liquid as one of its plates with a larger capacitance per unit volume than other types. They are valuable in relatively high-current and low-frequency electrical circuits. This is especially the case in power-supply filters, where they store charge needed to moderate output voltage and current fluctuations in rectifier output. They are also widely used as coupling capacitors in circuits where AC should be conducted but DC should not.

Electrolytic capacitors can have a very high capacitance, allowing filters made with them to have very low corner frequencies.

History

There is no clear inventor of the electrolytic capacitor. It is one of the many technologies that spent many years as a laboratory curiosity, a classic "solution looking for a problem".

The principle of the electrolytic capacitor was discovered in 1886 by Charles Pollak, as part of his research into anodizing of aluminum and other metals. Pollack discovered that due to the thinness of the aluminum oxide layer produced, there was a very high capacitance between the aluminum and the electrolyte solution. A major problem was that most electrolytes tended to dissolve the oxide layer again when the power is removed, but he eventually found that sodium perborate (borax) would allow the layer to be formed and not attack it afterwards. He was granted a patent for the borax-solution aluminum electrolytic capacitor in 1897.

The first application of the technology was in making starting capacitors for single-phase alternating current (AC) motors. Although most electrolytic capacitors are polarized, that is, they can only be operated with direct current (DC), by separately anodizing aluminum plates and then interleaving them in a borax bath, it is possible to make a capacitor that can be used in AC systems.

Nineteenth and early twentieth century electrolytic capacitors bore little resemblance to modern types, their construction being more along the lines of a car battery. The borax electrolyte solution had to be periodically topped up with distilled water, again reminiscent of a lead acid battery.

The first major application of DC versions of this type of capacitor was in large telephone exchanges, to reduce relay hash (noise) on the 48 volt DC power supply. The development of AC-operated domestic radio receivers in the late 1920s created a demand for large capacitance (for the time) high voltage capacitors, typically at least 4 microfarads and rated at around 500 volts DC. Waxed paper and oiled silk capacitors were available but devices with that order of capacitance and voltage rating were bulky and prohibitively expensive.

The ancestor of the modern electrolytic capacitor was patented by Julius Lilienfeld in 1926. Lilienfeld's design resembled that of a silver mica capacitor, but with electrolyte-soaked paper sheets in place of the mica dielectric. However, it proved impractical to adequately seal the devices, and in the hot conditions present inside typical AC operated radio receivers, the capacitors quickly dried out and failed.

Retired US Navy engineer Ralph D. Mershon is credited with developing the first commercially available "radio" electrolytic capacitor that was used in any quantity (although other researchers produced broadly similar devices). The "Mershon Condenser" as it was known (condenser being an earlier term for capacitor) was constructed like a conventional paper capacitor, with two long strips of aluminum foil inter-wound with strips of insulating paper, but with the paper saturated with electrolyte solution instead of wax. Rather than trying to hermetically seal the devices, Mershon's solution was to simply fit the capacitor into an oversize aluminum or copper can, half-filled with extra electrolyte. These units are referred to as "wet electrolytics," and those with liquid still inside are prized by vintage radio collectors.

"Mershons" were an immediate success and the name "Mershon Condenser" was, for a short time, synonymous with quality radio receivers in the late 1920s. However, due to a number of manufacturing difficulties, their service life turned out to be quite short and Mershon's company went bankrupt in the early 1930s.

It would not be until World War II, when sufficient resources were finally applied to finding the causes of electrolytic capacitor unreliability, that they became the reliable components they are today. A major advance was the process of etching and pre-anodizing the foil prior to assembly. This allowed the use of much less corrosive electrolyte solutions, which in turn meant the devices could be left unenergized for long periods without deterioration. Modern electrolytic capacitors can remain useable after lying idle for decades, whereas the original Mershons could not tolerate more than a few months without a polarizing voltage. Elaborate "re-forming" procedures were necessary to avoid damage to receivers that had not been used for some time.

Construction

Aluminum electrolytic capacitors are constructed from two conducting aluminum foils, one of which is coated with an insulating oxide layer, and a paper spacer soaked in electrolyte. The foil insulated by the oxide layer is the anode while the liquid electrolyte and the second foil act as cathode. This stack is then rolled up, fitted with pin connectors and placed in a cylindrical aluminium casing. The two most popular geometries are axial leads coming from the center of each circular face of the cylinder, or two radial leads or lugs on one of the circular faces. Both of these are shown in the picture.

Polarity

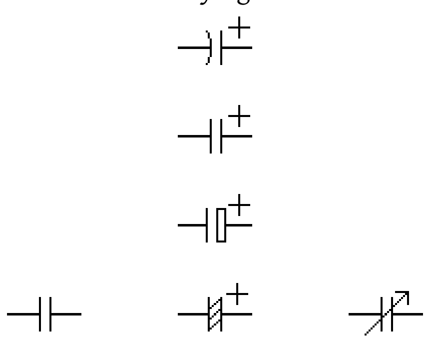
In aluminum electrolytic capacitors, the layer of insulating aluminum oxide on the surface of the aluminum plate acts as the dielectric, and it is the thinness of this layer that allows for a relatively high capacitance in a small volume. The aluminum oxide layer can withstand an electric field strength of the order of 10^9 volts per meter. The combination of high capacitance and high voltage result in high energy density.

Most electrolytic capacitors are polarized and may catastrophically fail if voltage is incorrectly applied. This is because a reverse-bias voltage above 1 to 1.5 V[1][2][3] will destroy the center layer of dielectric material via electrochemical reduction (see redox reactions). Following the loss of the dielectric material, the capacitor will short circuit, and with sufficient short circuit current, the electrolyte will rapidly heat up and either leak or cause the capacitor to burst. This is because, if the aluminium foil with a layer of aluminium oxide on it is made +ve the oxide ion will get oxidised and will convert into oxygen gas generating a high pressure and hence may burst up the capacitor. This is same as the electrochemical principle in an electrolytes with 2 electrodes.

To minimize the likelihood of a polarized electrolytic being incorrectly inserted into a circuit, polarity is indicated on the capacitor's exterior by a stripe with minus signs and possibly arrowheads adjacent to the negative lead or terminal. Also, the negative terminal lead of a radial electrolytic is shorter than the positive lead. On a printed circuit board, it is customary to indicate the correct orientation by using a square through-hole pad for the positive lead and a round pad for the negative.

Special capacitors designed for AC operation are available, usually referred to as "non-polarized" or "NP" types. In these, full-thickness oxide layers are formed on both the aluminum foil strips prior to assembly. On the alternate halves of the AC cycles, one or the other of the foil strips acts as a blocking diode, preventing reverse current from damaging the electrolyte of the other one. Essentially, a 10 microfarad AC capacitor behaves like two 20 microfarad DC capacitors in inverse series.

Modern capacitors have a safety valve, typically either a scored section of the can, or a specially designed end seal to vent the hot gas/liquid, but ruptures can still be dramatic. An electrolytic can withstand a reverse bias for a short period, but will conduct significant current and not act as a very good capacitor. Most will survive with no reverse DC bias or with only AC voltage, but circuits should be designed so that there is not a constant reverse bias for any significant amount of time.



Capacitor | Polarized Capacitor | Variable Capacitor

The above are the most common schematic symbols for electrolytic capacitors. Some schematic diagrams do not print the "+" adjacent to the symbol.

note: capacitors in a metal can have the color mark at the minus side.

Electrolyte

The electrolyte is usually boric acid or sodium borate in aqueous solution, together with various sugars or ethylene glycol which are added to retard evaporation. Getting a suitable balance between chemical stability and low internal electrical resistance is not a simple matter; in fact, the exact composition of high-performance electrolyte is a closely guarded trade secret. It took many years of painstaking research before reliable devices were developed. The electrolytic solvent has to have high dielectric constant, high dielectric strength, and low resistivity; a solute of ionic conductivity facilitators is mixed within.[4]

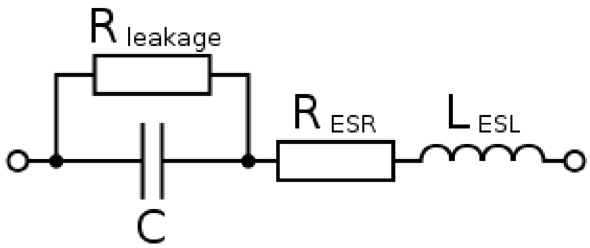
Electrolytes may be toxic or corrosive. Working with the electrolyte requires safe working practice and appropriate protective equipment such as gloves and safety glasses. Some very old tantalum electrolytics, often called "Wet-slug", contain corrosive sulfuric acid; however, most of these are no longer in service due to corrosion.

There are three major types of water-based electrolytes for aluminium electrolytic capacitors: standard water-based (with 40-70% water), and those containing ethylene glycol or dipropyl ketone (both with less than 25% water). The water content helps lowering the equivalent series resistance, but can make the capacitor prone to generating gas, especially if the electrolyte formulation is faulty; this is a leading cause of capacitor plague, to which the high water content electrolytes are more susceptible. The lower voltage ratings (thinner oxide layer) and lower operating voltage (slower regeneration of oxide layer) are further aggravating factors.[5]

There are a number of non-aqueous electrolytes, which use only small amount of water. The electrolytes are generally composed of a weak acid, a salt of weak acid, and a solvent, and optional thickening agent and other additives. The electrolyte is usually soaked into an electrode separator. The weak acids are usually organic acid (glacial acetic acid, lactic acid, propionic acid, butyric acid, crotonic acid, acrylic acid, phenol, cresol, etc.) or boric acid. The salts employed are often ammonium or metal salts of organic acids (ammonium acetate, ammonium citrate, aluminium acetate, calcium lactate, ammonium oxalate, etc.) or weak inorganic acids (sodium perborate, trisodium phosphate, etc.). Solvent-based electrolytes may be based on organic hydroxyl alkyl amines (monoethanolamine, diethanolamine, triethanolamine,...) or polyols (diethylene glycol, glycerol, etc.).[6]

Electrical behavior of electrolytics

A common modeling circuit for an electrolytic capacitor has the following schematic:



where R_{leakage} is the leakage resistance, R_{ESR} is the equivalent series resistance, L_{ESL} the equivalent series inductance (L being the conventional symbol for inductance).

R_{ESR} must be as small as possible since it determines the loss power when the capacitor is used to smooth voltage. Loss power scales quadratically with the ripple current flowing through and linearly with R_{ESR}. Low ESR capacitors are imperative for high efficiencies in power supplies.

It should be pointed out that this is only a simple model and does not include dielectric absorption (soakage) and other non-ideal effects associated with real electrolytic capacitors.

Since the electrolytes evaporate, design life is most often rated in hours at a set temperature. For example, typically as 2000 hours at 105 degrees Celsius (which is the highest working temperature). Design life doubles for each 10 degrees Celsius lower[1], reaching 15 years at 45 degrees Celsius. However a great number of capacitors much older than this are still in service. Most Electrolytic capacitors are rated for 85 degrees Celsius maximum.

Capacitance

The capacitance value of any capacitor is a measure of the amount of electric charge stored per unit of potential difference between the plates. The basic unit of capacitance is a farad; however, this unit has been too large for general use until the invention of the double-layer capacitor, so microfarad, nanofarad and picofarad are more commonly used. These are usually abbreviated to μF (or uF), nF, and pF.

Many conditions determine a capacitor's value, such as the thickness of the dielectric and the plate area. In the manufacturing process, electrolytic capacitors are made to conform to a set of preferred numbers. By multiplying these base numbers by a power of ten, any practical capacitor value can be achieved, which is suitable for most applications.

A standardized set of capacitor *base numbers* was devised so that the value of any modern electrolytic capacitor could be derived from multiplying one of the modern conventional base numbers **1.0**, **1.5**, **2.2**, **3.3**, **4.7** or **6.8** by a power of ten. Therefore, it is common to find capacitors with values of 10, 15, 22, 33, 47, 68, 100, 220, and so on. Using this method, values ranging from 0.1 to 4700 are common in most applications. Values are generally in microfarads (µF).

Many electrolytic capacitors have a *tolerance* range of 20%, meaning that the manufacturer is stating that the actual value of the capacitor lies within 20% of its labeled value. Selection of the preferred series ensures that any capacitor can be sold as a standard value, within the tolerance. Also many electrolytic caps have asymmetric tolerances, typically -20% but with much larger positive tolerance. This eliminates any need to test and grade individual caps.

Variants

Electrolytic capacitors of several sizes

Unlike capacitors that use a bulk dielectric made from an intrinsically insulating material, the dielectric in electrolytic capacitors depends on the formation and maintenance of a microscopic metal oxide layer. Compared to bulk dielectric capacitors, this very thin dielectric allows for much more capacitance in the same unit volume, but maintaining the integrity of the dielectric usually requires the steady application of the correct polarity of direct current else the oxide layer will break down and rupture, causing the capacitor to lose its ability to withstand applied voltage (although it can often be "reformed"). In addition, electrolytic capacitors generally use an internal wet chemistry and they will eventually fail if the water within the capacitor evaporates.

Electrolytic capacitance values are not as tightly-specified as with bulk dielectric capacitors. Especially with aluminum electrolytics, it is quite common to see an electrolytic capacitor specified as having a "guaranteed minimum value" and no upper bound on its value. For most purposes (such as power supply filtering and signal coupling), this type of specification is acceptable.

As with bulk dielectric capacitors, electrolytic capacitors come in several varieties:

- : compact but lossy, these are available in the range of <1 µF to 1 F with working voltages up to several hundred volts DC. The dielectric is a thin layer of aluminum oxide. They contain corrosive liquid and can burst if the device is connected backwards. The oxide insulating layer will tend to deteriorate in the absence of a sufficient rejuvenating voltage, and eventually the capacitor will lose its ability to withstand voltage if voltage is not applied. A capacitor to which this has happened can often be "reformed" by connecting it to a voltage source through a resistor and allowing the resulting current to slowly restore the oxide layer.[7] Bipolar electrolytics (also called Non-Polarised or NP capacitors) contain two capacitors connected in series opposition and are used when the DC bias voltage must occasionally reverse. Bad frequency and temperature characteristics make them unsuited for high-frequency applications. Typical ESL values are a few nanohenries.[8]
- : compact, low-voltage devices up to several hundred µF, these have a lower energy density and are more accurate than aluminum electrolytics. Tantalum capacitors are also polarized because of their dissimilar electrodes. The cathode electrode is formed of sintered tantalum grains, with the dielectric electrochemically formed as a thin layer of oxide. The thin layer of oxide and high surface area of the porous sintered material gives this type a very high capacitance per unit volume. The cathode electrode is formed either of a liquid electrolyte connecting the outer can or of a chemically deposited semi-conductive layer of manganese dioxide, which is then connected to an external wire lead. A development of this type replaces the manganese dioxide with a conductive plastic polymer (polypyrrole) that reduces internal resistance and eliminates a self-ignition failure.[9]

  Compared to aluminum electrolytics, tantalum capacitors have very stable capacitance, little DC leakage, and very low impedance at high frequencies. However, unlike aluminum electrolytics, they are intolerant of voltage spikes and are destroyed (often exploding violently) if connected in the circuit backwards or exposed to spikes above their voltage rating.

Tantalum capacitors are more expensive than aluminum-based capacitors and generally only usable at low voltage, but because of their higher capacitance per unit volume and lower impedance at high frequencies, they are popular in miniature applications such as cellular telephones.

Reliability and length of life.

Aluminum electrolytics have their problems however; noise, high leakage, high temperature drift, high dielectric absorption and high inductance. Additionally, low temperature is a problem for most aluminum capacitors. For most types, capacitance falls off rapidly below room temperature while dissipation factor can be ten times higher at −25 °C than at 25 °C. Most limitations can be traced to the electrolyte. At high temperature, the water can be lost to evaporation, and the capacitor (especially the small sizes) may leak outright. At low temperatures, the conductance of the salts declines, raising the ESR, and the increase in the electrolyte´s surface tension can cause reduced contact with the dielectric. The conductance of electrolytes generally has a very high temperature coefficient, +2%/°C is typical, depending on size. The electrolyte is implicated in various reliability issues as well. [2]

See also

- Capacitor plague
- Supercapacitor

References

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[2] Electrolytic capacitors (Barry L. Ornitz)
[3] Product Information: Aluminum Electrolytic Capacitors FAQ/Capacitor, Power Supply Units RUBYCON CORPORATION
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[5] TTI Europe - Aluminium Electrolytic Capacitors Failing Again
[6] FaradNet: "Electrolytic Capacitors", chapter 10
[7] Reforming Electrolytic Capacitors.
[8] The effect of non-ideal capacitors. Murata technical document.
[9] NIC components Corp. FAQ

- Glenn Zorpette (January 2005). "Super Charged: A Tiny South Korean Company is Out to Make Capacitors Powerful enough to Propel the Next Generation of Hybrid-Electric Cars". *IEEE Spectrum* **42** No. 1. http://spectrum.ieee.org/jan05/inthisissue.
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External links

- Article at CWRU
- How Electrolytic Capacitors Work
- How to Identify Japanese Electrolytic Capacitors

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