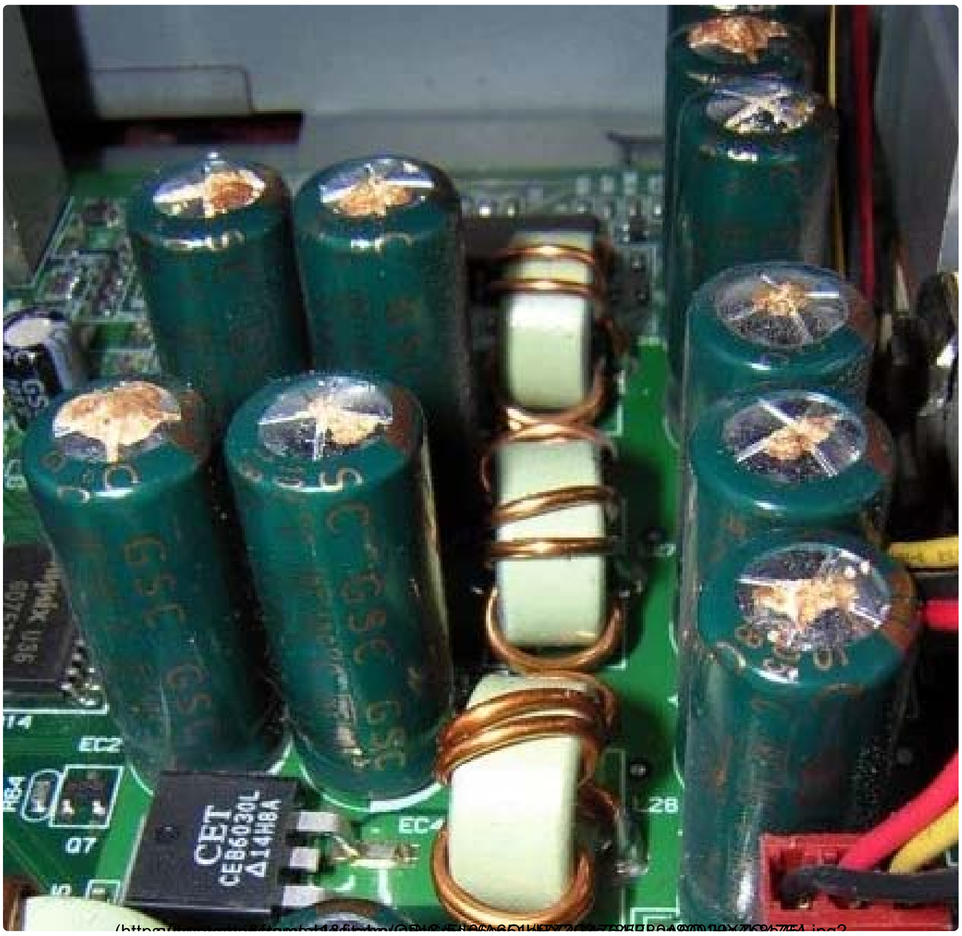
Measuring Capacitor Health (tan Δ Vs ESR)



One of the leading causes of early device death for electronics is the failure of one or more capacitors in the power supply. This is doubly true for devices that see high currents, run hot or have their boards in enclosed spaces. Devices such as LCD/Plasma TV's, computer power supplies and even older computer motherboards are often afflicted with failed capacitors .

Bad capacitors can often manifest themselves with ruptured vents or leaking electrolyte around the base. The latter can be exceptionally bad because the electrolyte is highly conductive, as well as corrosive. It can eat through the insulating layer on a board bridging traces which can result in permanent damage, or worse, a fire Unfortunately, capacitors don't always fail with visible symptoms.

Repairing devices with bad capacitors is often a great and easy way to score electronics devices at a huge discount. This is especially true for televisions. If the TV is a few years old and all of a sudden starts failing power-on there is a HIGH chance that capacitors in the power supply have gone bad.

Add Tip Ask Question Comment Download

Step 1: Why Do Capacitors Fail?

In this image we can see a capacitor which has failed. The cross-hatch in the image is a special safety vent which is designed to rupture if the internal pressure gets too high. This high pressure is caused by the generation of various gases like hydrogen as the capacitor fails and the electrolyte breaks down. There are a variety of reason why electrolytic capacitors fail. These failures can typically be broken down into five distinct reasons:

I. Age

Capacitors have a finite lifetime. They are typically rated for a certain number of hours at or below a particular temperature. As they get used, over time, they tend to wear out; eventually failing. This is the most common means of capacitor failure in equipment that is decades old. Quite simply, the capacitors have lived their lives and are dying a natural death.

II. Heat

One of the biggest enemies of electrolytic capacitors is heat! Heat causes the internal electrolyte to dry out over time causing the capacitor fail. This is one of the main reasons that capacitors placed near heat sinks typically fail 'prematurely'. A capacitor rated for 2000h at 85oC, has a life of only 500h at 105oC and only 125h at 125oC. Keep in mind, 2000h is only 83 days of 24/7 usage. Luckily, keeping the capacitors at a lower temperature extends their life in much the same way. THIS is what most designers hope to exploit to ensure a longer life.

III. Excessive ripple

This is not something that the end-user can change or typically even has the equipment to measure. It is a decision made in the design phase of the board. All capacitors have a designated amount of ripple current they can handle. If this value is exceeded then the capacitor can become excessively heated internally. As mentioned before, heat is the enemy of capacitors. Capacitors capable of handling high ripple currents are expensive so sometimes lower grade parts are used to cut costs.

IV. Industrial Espionage

This was a huge issue at the turn of the millennium. A scientist at a Japanese capacitor firm stole an electrolyte formula and took it back to a Taiwanese firm where it was sold. This formula was resold to a variety of budget capacitor makers and was the reason for the "capacitor plague (http://en.wikipedia.org/wiki/Capacitor_plague)" which killed thousands of computers around that time period. Failures were incredibly wide spread and is the reason that Japanese capacitors are still to this day a bullet point on high-end motherboards. As a side note, this only affected Taiwanese manufacturers and should should not be confused with another issue that cropped up at around the same time with Nichicon/United Chemicon capacitors. NCC/UCC capacitors had an issue where they were over-filled with electrolyte causing them to rupture.

V. Abuse

While capacitors are much more robust than most semiconductor deices, they can be abused. They don't like huge over voltages, they don't like heavy mechanical forces and they often are sensitive to chemical exposure. The most common form of abuse is voltage spikes. Large voltage spikes can poke holes in the internal insulating layers of the capacitor. Once this insulating layer is breached, the capacitor has a dead short from one plate to the other. This typically results in a rapid catastrophic death. You could argue that excessive ripple falls under this category as well because the capacitor is being abused with more than its rated abilities.

Step 2: Spotting Bad Capacitors

In order to fix them, you have to find them.

Locations

Failed capacitors are most commonly found in the power supplies of a device; either in the main supply or secondary voltage supplies. They fail because they are used for filtering large amount of ripple and noise from the supply. This places the capacitor under high stress, making them much more prone to failure. These filter capacitors are typically the largest capacitors on the board having values in the 100's to 1000's of microfarads (uF). Much smaller capacitors, 10's of uFs or less, are typically decoupling capacitors and are much less prone to failure. These capacitors are not stressed nearly as much as the filter capacitors. Only check these if you all of the main suspects have been eliminated.

Visual characteristics

- a bulging or ruptured top
- a distended bung - the actual name for the plastic insert in the base of a capacitor
- leaking electrolyte at the base
- a brown spot at the vents where the electrolyte has started to leak
- an exploded capacitor

In the above image the bulging/domed top is clearly visible. Additionally, on two of the capacitors, the black bung is being pushed out of the bottom due to high internal pressure. When the bung fails, electrolyte typically leaks on to the board. These are the typical visible indicators of failure. If even one capacitor in a group is showing signs of failure, you should replace ALL of the capacitors in the group as they are all suspect.

Unfortunately, a high percentage of caps fail with no external indication at all. We have to test these caps with non-visual means.

Add Tip Ask Question Comment Download

Step 3: Measuring the Health.

$$\tan\delta = \frac{\mathrm{ESR}}{|X_c|} = \mathrm{DF}$$

Many people believe that you can simply measure the capacitance of a capacitor to determine its health. Unfortunately, this is not the case. Most systems will fail long before the capacitor shows any appreciable change in its bulk capacitance. Instead we are left with two main means of testing the 'health' of a capacitor. These methods are measuring ESR and measuring *tan δ*. Mathematically these two values are related by the formula in the above image.

ESR is an abbreviation for *equivalent series Resistance*. While an ideal capacitor would have zero loses in a circuit, a real capacitor is better approximated as an ideal capacitor in series with a small resistor. As a capacitor starts to fail, typically the value of this resistance increases over time. By measuring it against set values we can approximate the health of a capacitor.

tan δ also called dissipation factor, abbreviated DF or D. As shown in the formula of the image, it is the ESR divided by the reactance of the capacitor. Reactance is the resistance of a capacitor to a change in voltage. Reactane is frequency dependent, so *tan δ* values are often specified at a given frequency (typically 120Hz).

Add Tip Ask Question Comment Download

Step 4: Measuring ESR - the Benefits and Drawbacks

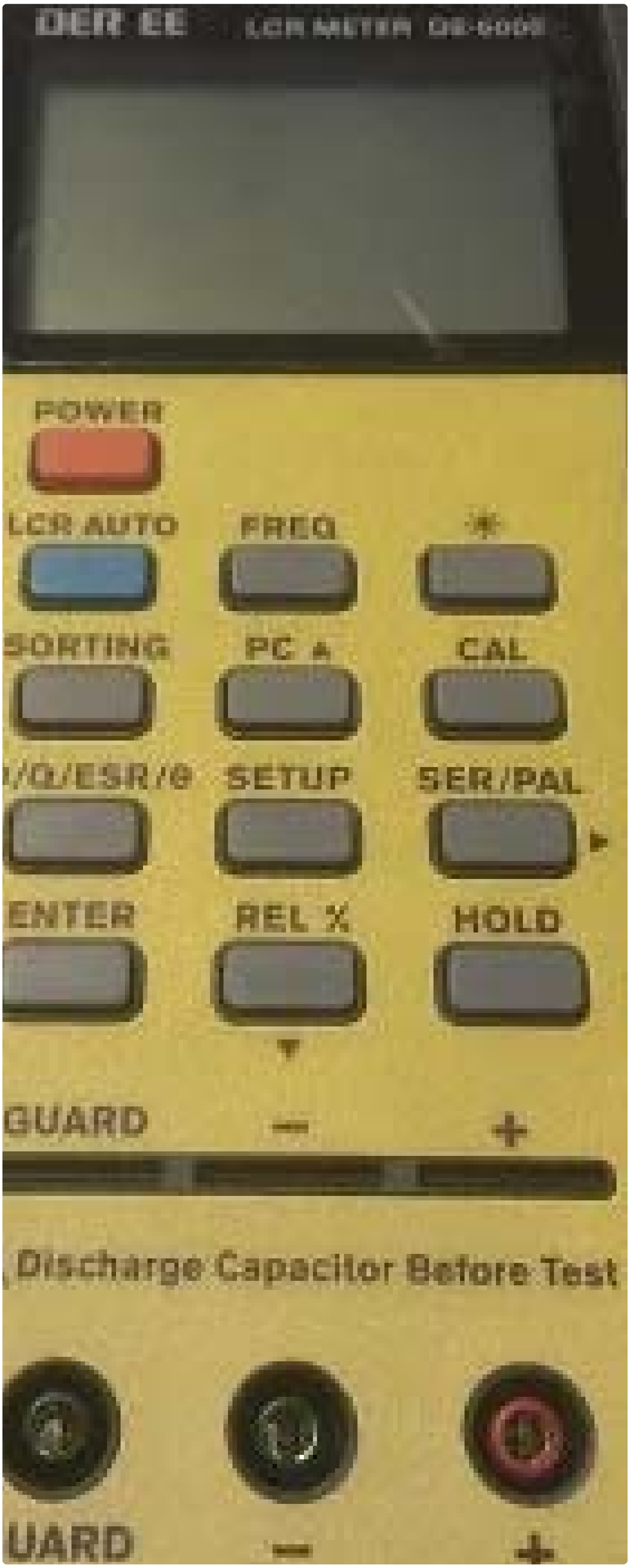
Measuring ESR has a variety of benefits, the foremost of which is the availability of cheap ESR meters. It is not uncommon to find cheap ESR meters for US$20 or less. They come in a variety of sizes and formats, though they typically always show the capacitance and the ESR value. The accuracy of these meters tends to be questionable but because the judgements made are qualitative, extreme accuracy is not necessary.

Typically determining capacitor health is done by measuring the ESR and comparing it to am ESR table, such as the one right here (http://www.jestineyong.com/wp-content/uploads/2012/05/ESRTable1.jpg). These tables are compiled by taking the average of readings of multiple good capacitors. By comparing it to a table of averages, you can determine the health of the capacitor against a known value. If it is above the value, it is suspect and should be replaced, below the value it should be OK. It is this combination of low cost and ease of use that has made ESR measurements so popular.

In the second image, we see the ESR being measured on a 35v 560uF capacitor. Based on the table, a good capacitor should fall around 0.1 ohms or less. This capacitor has an ESR of 0.1 ohms so it is still healthy.

Unfortunately, it is not without its drawbacks. First and foremost, capacitors which are starting to fail short, instead of fail open, will show a low ESR. Decreasing until the ESR eventually reaches near zero (a dead short). Second, it ahas a tendency to be very unreliable below ~4.7uF. Third, this method compares the ESR reading against an average value. Modern electrolytic capacitors tend to exist in a wide range (Standard, Low-ESR, ultra low-ESR, etc.). So a failing low-ESR capacitor might still appear OK because the number it is compared against is an average of ALL types. To compound this matter, ESR is typically not discussed in a capacitors datasheet. Leaving the ESR tables as the only source of reference.

Step 5: Measuring Tan Δ



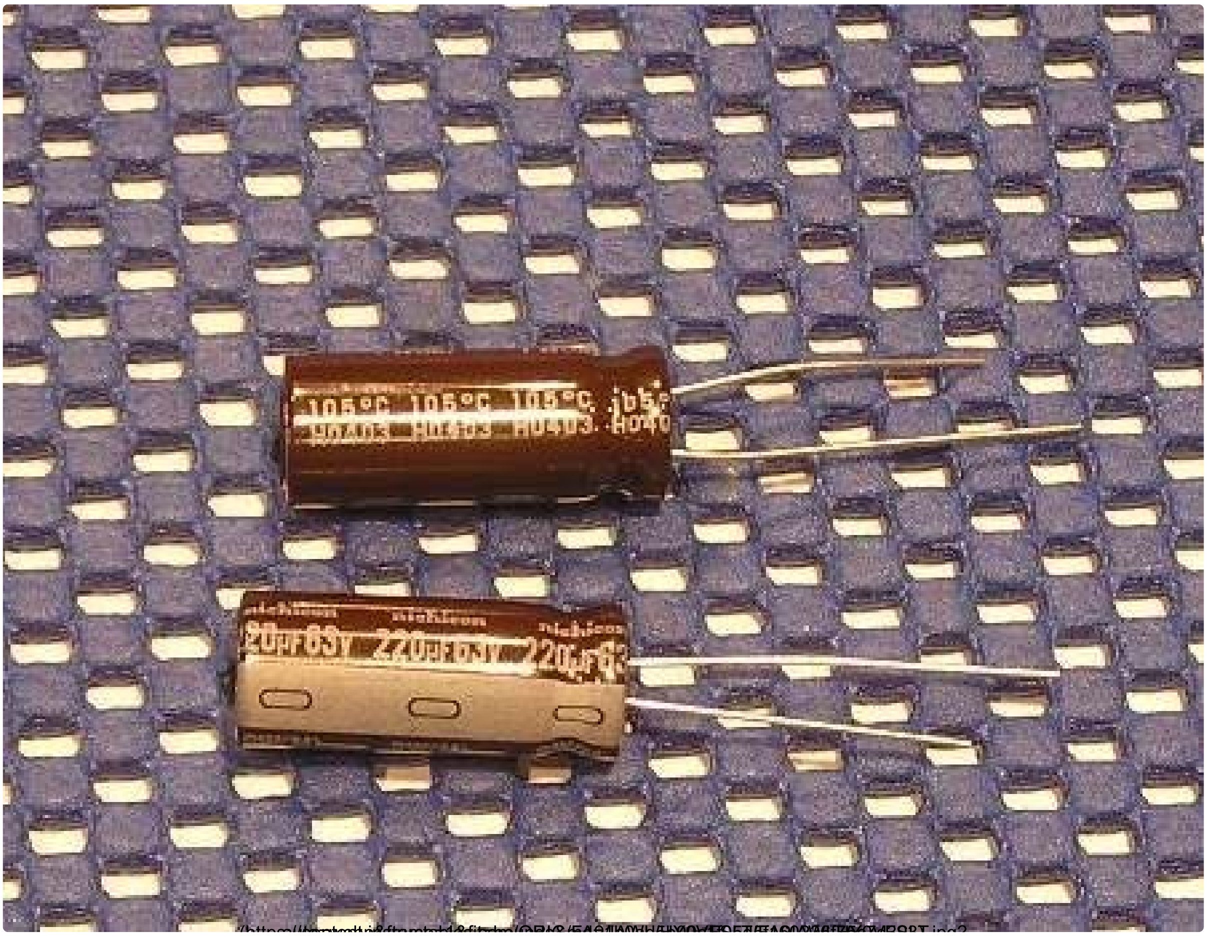
Measuring *tan δ* is a much less commonly discussed topic. Mainly because, until recently, it was not an affordable means of measuring capacitor health for the hobbyist/end user. Quite simply, ESR was the only game in town. In the past few years, prices have dropped from over $1000 to under $100. Measuring tan δ requires a specialized instrument called an LCR meter. This instrument should not be confused with LCRs that are actually multimeters in disguise. True LCR meters are capable of measuring parameters such as ESR, Q, tan δ(D) at a variety of frequencies (up to 100kHz). Examples include the Der EE DE-5000 (shown above), Uni-T UT612 and the Agilent U1733C.

Despite it's increased cost, measuring *tan δ* though gives us a variety of benefits over a simple ESR measurement. First and foremost, it is in nearly every capacitor datasheet. This means that when we test the health of a specific capacitor we can compare it directly to a manufacturers spec. We can evaluate it against the same parameters that the circuit designer was evaluating it against. No matter the type of electrolytic capacitor, we will have a precise factory determined value to compare it against. Typically the datasheet listing for tan δ will list the voltage of the capacitor, the frequency to test at and any caveats.

The third image, illustrates why ESR by itself can be a bad measurement of health. The capacitor under test is a standard, small size, audio grade capacitor. This capacitor was purchased directly from an authorized distributor. It has an ESR of 168.9 ohms at 120Hz. Instinct would be to say, there is NO WAY that capacitor is healthy. By testing tan δ(D), a different picture emerges, a value of 0.013. Comparing it to the values in the datasheet (http://www.nichicon.co.jp/english/products/pdfs/e-fw.pdf) at 100V, we discover it is actually quite healthy. D is actually less than the max new value of 0.08 and well below the end-of-life value of 0.16. The end-of-life value is often called the endurance value and is typically rated as a certain percentage of the initial maximum value.

It is this ease of looking up a value in the datasheet that makes tan δ so valuable. It is just as easy to check as ESR, but there is no more checking against arbitrary values in an averages table. It's just definitive values in a datasheet made by the manufacturer. The last image shows a typical tan δ table from a capacitor datasheet (specifically the Panasonic FM capacitor).

Step 6: Finding Replacement Capacitors



First and foremost, I must say DO NOT ORDER FROM EBAY. I would say EASILY 95+% of the capacitors on ebay are outright fakes. For some models (like Rubycon BlackGates) that number is likely closer to 100%. Yes, the prices look great, compared to more official sites but there is a reason for that. Most are fake.

A few sites to use, this is far from an encompassing list but is a good starting point:

- http://www.digikey.com (http://www.digikey.com)
- http://www.mouser.com (http://www.mouser.com)
- http://www.newark.com (http://www.newark.com)
- http://www.arrow.com (http://www.arrow.com)

Brands to look for:

- Nichicon
- United Chemicon (sister company to Nichicon)
- Rubycon
- Panasonic (also called Matsushita)
- Elna
- Vishay/Spraque

A few tips on selecting the right capacitor for the circuit. First and foremost try to match both the voltage and capacitance spec. If this is not possible, go up in capacitance and/or voltage, never down. If you need a 16V 2000uF capacitor, a 16V 2200uF would be acceptable as would a 20V 2000uF. Always try to use 105oC or higher capacitors, even if the original parts are 85oC; this will increase their lifetime. As a good rule of thumb, almost always select a low-esr capacitor. This is especially true if the values are in the 100's of uF or more. As mentioned before, these caps often serve filtering functions and are the first to die. A low-ESR capacitor will live a much longer life in this role.

One exception to the low-esr rule is decoupling caps, which often have values in the 10's of uF and are located near voltage regulators, these should be standard caps. Low-ESR caps for decoupling can cause the voltage regulator to oscillate due to instability. The voltage regulator actually expects a bit of resistance from the capacitor to help stabilize the circuit. These don't as commonly need replacing (other than for age) but it is good to keep in the back of your mind.

Good luck and hopefully you can save some equipment from the junk pile. Remember, every device repaired is another device that isn't destined to pollute the environment. If you have any questions on capacitor selection, LCR selection, etc. feel free to ask them in the comments.

Image courtesy of LGreen - under GNU Free Documentation License (http://en.wikipedia.org/wiki/GNU_Free_Documentation_License)