Measuring ESR

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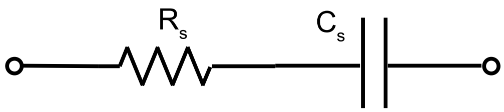
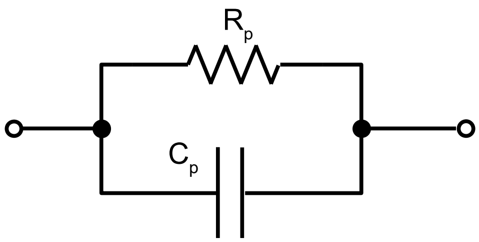
Capacitors are often modeled as a pure capacitance in series with a resistance[1]. This series resistance is called ESR for "equivalent series resistance". This becomes an important measure for e.g. large electrolytic capacitors used for filtering duty in power supplies -- the ESR dissipates power. Here's the model:



The ESR is the resistance R_s. The series model can be transformed into a parallel model [7]:



from a resistor R_p and pure capacitance C_p in parallel. Either model's impedance is (complex values are shown in ***this font***):

$$\mathbf{Z} = R_s + \frac{1}{\mathbf{j}\omega C_s} = \frac{\dfrac{R_p}{\mathbf{j}\omega C_p}}{R_p + \dfrac{1}{\mathbf{j}\omega C_p}} = \frac{D^2 R_p + \dfrac{1}{\mathbf{j}\omega C_p}}{1+D^2}$$

where the capacitor's dissipation factor D is

$$D = \frac{\text{ESR}}{\text{reactance of } C_s} = \omega R_s C_s = \frac{1}{\omega R_p C_p}$$

and this can be used to relate the parallel and series model's capacitances:

$$C_s = (1+D^2) C_p$$
$$C_p = \frac{1}{1+D^2} C_s = C_s \sin^2\theta$$

where θ is the phase angle of the impedance and

$$R_s = \text{ESR} = \frac{D^2}{1+D^2} R_p = \frac{D}{\omega C_s} = Z\cos\theta$$
$$R_p = \frac{1+D^2}{D^2} R_s = \frac{1}{\omega C_p D}$$

(where $Z = |\mathbf{Z}|$), which shows the ESR is frequency-dependent.

Depending on the capacitor's value, you typically want to see the ESR of a capacitor well below 1 Ω, preferably in the mΩ region, at least for the big filter caps. As capacitors age, the ESR may go up,

1 This is a model, not an exact representation of a real capacitor. Other effects like inductance become important as the frequency increases and things like dielectric absorption befuddle the simple models.

increasing the operating temperature of the capacitor and increasing the rate of degradation. When fixing broken older electronic equipment, experienced troubleshooters will often check the capacitors first, as they are a common failure mode (besides being relatively easy to replace). A good test is to use a meter that measures ESR and look for an ESR value that is too high. An advantage is that **the capacitor's ESR can be tested in-circuit**. This is because a mΩ-level ESR will probably short out any other components around it except for wires or PC board traces.

Commercial meters that measure ESR can be expensive if you don't use them very often. Your digital multimeter is useless because that capacitance will block DC if you try to measure the DC resistance. We'll look at an easy way of estimating ESR with test equipment you may already have.

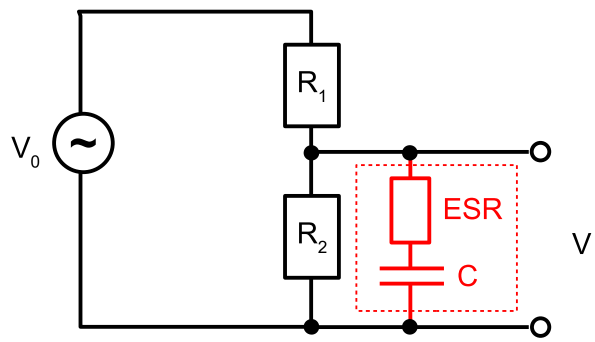


Figure 1

To check a capacitor's ESR, here's the basic test circuit:

An AC voltage source supplies a voltage V_0 to a voltage divider composed of R_1 and R_2. First, imagine that the red capacitor with ESR is not present. Then the output voltage V is

$$V_{\text{div}} = \frac{R_2}{R_1 + R_2} V_0$$

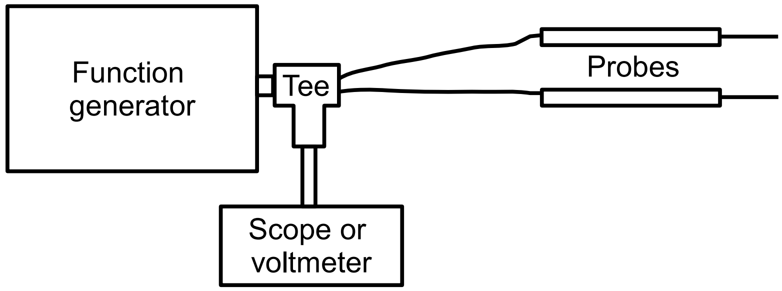
Now, if the red capacitor is put into the circuit, the impedance of the ESR and the capacitor is in parallel with R_2. For an AC signal, the reactance of C will be small if C is a reasonably large capacitor. This shorts out R_2 and causes the output voltage V to drop. Call this second "shorted" output voltage V_s. Then if the ESR is small, we have

$$V_s \ll V_{\text{div}}$$

Conversely, if the ESR is large (or the reactance of C is large), then V_s will be about the same as V_{div}.

This is how an approximate ESR measurement can be made. V_0 can be supplied by a function generator (or a transformer) and V_{div} and V_s can be measured by a voltmeter or scope. If you'll be testing power supply capacitors, you could get V_0 using a filament transformer, but the advantage of a function generator is that you can test the capacitor at higher frequencies. As you increase the frequency, the reactance drops but the ESR isn't affected as much. With a low reactance, the shorting out of R_2 is dominated by the ESR. ESR meters often use 100 kHz as a test frequency.

Now, you don't really need to construct a voltage divider -- but the voltage divider would let you e.g. use a transformer or other signal source that you didn't have control over the output voltage. The easiest method is to use a function generator. Connect two probes to a tee as shown in the following figure and you can start probing capacitors to estimate their ESR.



Here's the basic method. Set the function generator to output a sine wave at a convenient voltage as measured by the scope or voltmeter. 1 Vrms at 1 kHz might be convenient. Now, probe a capacitor to estimate its ESR. The more the voltage drops, the lower the ESR and/or the capacitive reactance. **A high capacitance capacitor with a large ESR will give itself away by not dropping the voltage much**. If you don't have a function generator, you can build a suitable oscillator. See reference [2] for a possible circuit diagram.

Find some resistors with values of approximately 0.1, 1, 10, and 100 ohms. Use these to get a rough calibration of the voltage measurement. Then when you measure an ESR with about the same voltage drop, you can estimate the value of the ESR. Note this works better for higher frequencies where the capacitor's reactance is negligible. Thus, people often test ESR at frequencies on the order of 10 to 100 kHz. Plot a chart of the measured voltage amplitude as a function of the known resistance and you can use this chart to make a guess as to a capacitor's ESR. This test is mainly aimed at the big electrolytic capacitors in a circuit, as these are the ones that are failure-prone.

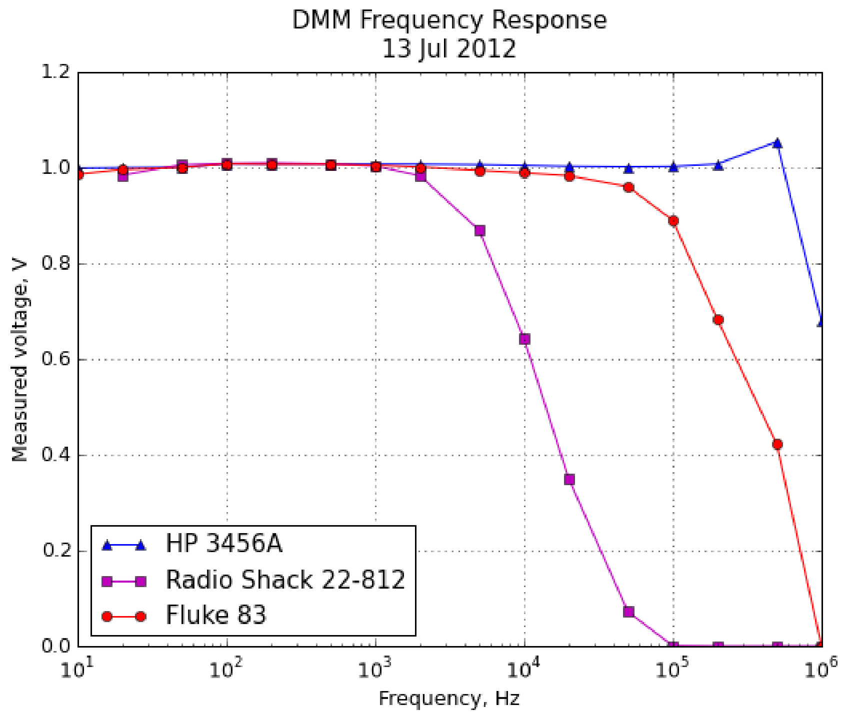
Here's a table of voltages I made using a General Radio resistance box with a test sine wave of 100 kHz:

Resistance, Ω	Scope voltage, Vpp	Fluke 83 voltage at 10 kHz
10 k	1.00	1.00
1 k	0.96	0.957
100	0.67	0.666
10	0.176	0.167
1	0.006	0.0206
0.1	*	0.0033

Table 1

The * means there was no way to distinguish the measurement from noise. You can see from these numbers that you'll likely be able to detect an ESR of a big capacitor that's a few ohms or more relatively easily. Since these big capacitors should have ESRs in the mΩ region, a bad one should stand out quickly. Remember, you're using two probes; you quickly probe each big capacitor in the circuit and look for a sine wave signal on the scope. Basically, **a noticeable sine wave makes you suspicious about a big capacitor's ESR**. If you're using a voltmeter, a measured voltage of 20 mV or more might make you suspicious.

You might want to check the AC bandwidth of your digital multimeter -- it may be a suitable tool for making these measurements if you don't have a scope. Many DMMs can make useful comparative measurements to 10 kHz or more, even if the sine wave's frequency is beyond the rated bandwidth of the meter. My Fluke 83 DMM is only specified to 5 kHz for AC voltage measurements, but it worked just fine as indicated in Table 1 above. Here's a plot of its frequency response compared to an HP 3456A voltmeter (I also included a Radio Shack 22-812 DMM I have):



I wouldn't hesitate to use the Fluke for comparative measurements up to 100 kHz and the Radio Shack meter would be usable at 10 kHz for comparisons. To make these measurements, I used a B&K 4076 function generator, which is specified to be flat to 0.1 dB (i.e., about 1%) over this frequency range.

You may want to make up a table of reactance as a function of capacitance for the frequency you plan to use. This will give you an idea of the reactance part of the capacitor's impedance, helping you guess how much the voltage drop is due to ESR versus reactance. Here's one such table:

	Reactance in Ω at indicated frequency			
Cap.	**100 Hz**	**1 kHz**	**10 kHz**	**100 kHz**
10 nF	159155	15915	1592	159
100 nF	15915	1592	159	15.9
1 µF	1592	159	15.9	1.59
10 µF	159	15.9	1.59	0.159
100 µF	15.9	1.59	0.16	0.016
1 mF	1.59	0.16	0.016	0.002
10 mF	0.16	0.016	0.002	0.0002

The disadvantage of this method is that you can't really distinguish a voltage drop caused by the real or imaginary part of the impedance (the scope or voltmeter is measuring the complex voltage's magnitude). However, looking at the reactances in the colored boxes in the table shows that testing large capacitors at 10 or 100 kHz should be mostly like looking at a dead short. Since the measurement of ESR is probably mostly used to troubleshoot bad large capacitors in circuits, a conclusion you might make is to test at 10 or 100 kHz and just **look for those big capacitors that don't look like a dead short**. These may have high ESR.

An advantage of using a digital scope is that you can set the function generator to e.g. 250 mVpp and use the scope's averaging ability to average out much of the noise the leads will pick up. This voltage is low enough not to turn on any semiconductor junctions, meaning you can test in-circuit.

If you'll be making these measurements frequently, you might want build a special test circuit for convenience. Search the web (use "ESR tester" or something similar) and you'll get a number of pages showing various circuits and techniques (a nice-looking project is [2] in the references).

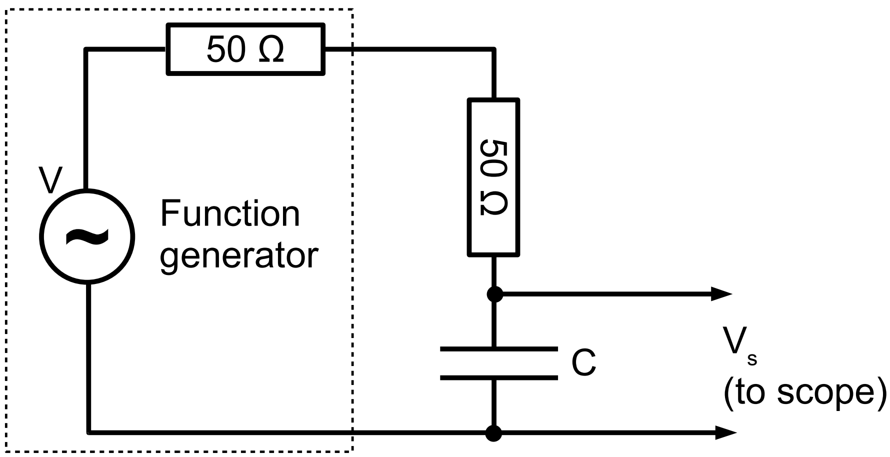
Some cautions are in order when using this test method:

1. Always make sure the capacitor is discharged before measuring its ESR (be careful of dielectric absorption effects too if appropriate).
2. A shorted capacitor will appear to be a good capacitor with this test. If you measure a very low ESR for a capacitor, you need to make sure it isn't a shorted capacitor. Check its capacitance with your DMM if it can measure capacitance. Otherwise, you can try measuring the DC resistance. The problem with this resistance measurement is that a big discharged capacitor looks like a dead short to your resistance measurement -- and your DMM doesn't supply enough current to charge the capacitor to the point that the current will drop and the measured resistance will go up. Thus, if you still suspect the capacitor is shorted, you might have to remove it from the circuit and see if you can charge it up with a DC voltage from a power supply.

   I've never run across a shorted capacitor, but from things I've read on the web, it appears a shorted capacitor will also bulge or leak.

Alternative method using a short pulse

Reference [5] gives another method of using a scope and function generator to estimate ESR. Use the following circuit:



For a capacitor C with a low ESR, this is approximately a voltage divider such that the voltage going to the scope is

$$V_s = \frac{\text{ESR}}{100} V$$

where ESR is the capacitor's equivalent series resistance and we're ignoring the reactance. Solving for ESR gives

$$\text{ESR} = 100 \frac{V_s}{V}$$

The reason why we can ignore the reactance is that we use the function generator to apply a 1 μs wide pulse to the capacitor[2]; since this pulse involves frequencies of 1 MHz and above, the reactance will be ignorable. The capacitor won't have time to charge (the RC time constant for a 10 μF capacitor with a 100 ohm resistance is 1 ms), so **the voltage you see across the capacitor is due to the ESR**. Here's a scope trace of the pulse resulting from testing a 10.9 μF tantalum capacitor that had an ESR of 1.2 Ω measured by an LCR meter at 1 kHz.

2 Use a reasonably low repetition rate like 1 kHz or so.

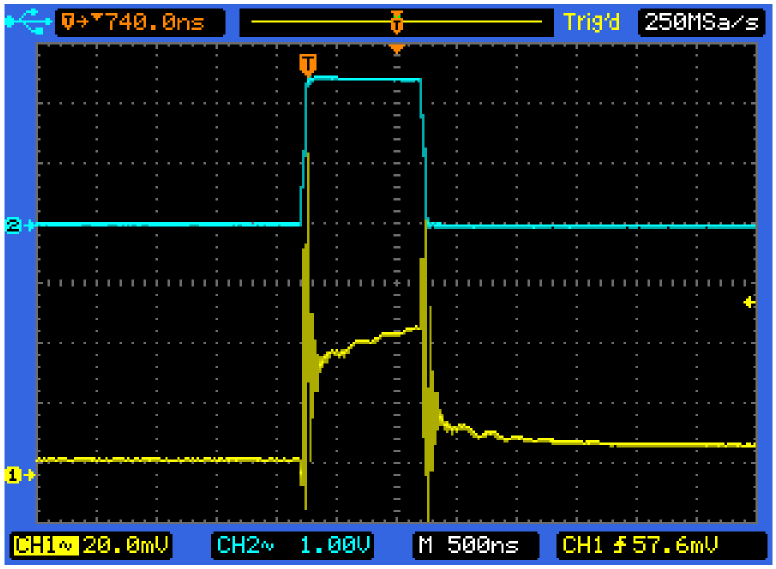


Figure 2

The blue trace on the top is the voltage applied by the function generator -- the pulse height is 2.4 volts. The yellow trace is V_s and roughly starts at about 30 mV. By the above formula, this gives us an ESR of 100(0.03/2.4) or 1.25 Ω.

The ringing on the edges comes from the leads used to make the connections and confuses the ESR estimate. The measurement abilities would likely be improved if a test fixture with coaxial leads and proper terminations was used. However, since most of the time we just want an estimate of ESR to about one significant figure, this more ad hoc method may be adequate.

A capacitor story

When I was a TA, one of the teachers liked a demo I had shown him. This involved a rack of 600 V capacitors; each capacitor was about half again larger than a soft drink can. There were about 16 of these capacitors on the rack. I used a big old vacuum tube Sorenson power supply that would charge this capacitor bank up to around 400 V. The demo was to short the heavy bus bars of the rack with a screwdriver. This gave a flash of light and a surprising bang which sounded like a gunshot. It would invariably make a few of the girls in the lecture hall scream because it was so unexpected. That screwdriver still has a number of marks on it where the electrical energy blasted a small divot in the metal.

References

[1] http://repairfaq.ece.drexel.edu/sam/captest.htm#ctesr

[2] http://members.shaw.ca/swstuff/esrmeter.html

[3] http://en.wikipedia.org/wiki/Equivalent_series_resistance

[4] http://bama.edebris.com/manuals/gr/1650b/

[5] http://geoffg.net/Measuring_ESR.html

[6] http://ludens.cl/Electron/esr/esr.html

[7] ImpedanceFormulas.pdf at https://someonesdad1.github.io/hobbyutil/project_list.html.

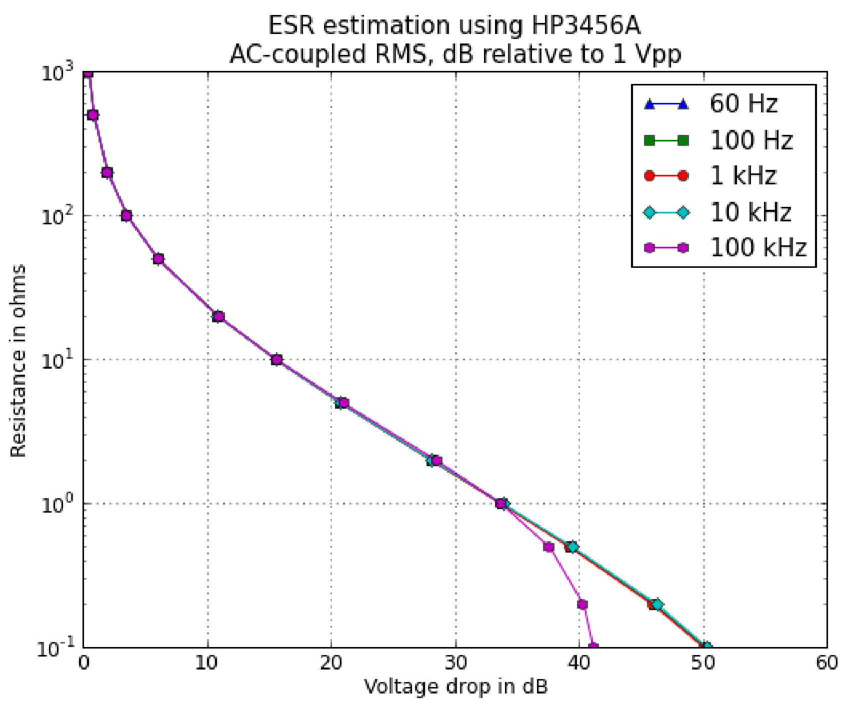
New stuff (Apr 2013)

Set up the 3456 to read dB relative to some open circuit voltage of a sine wave (say, 1 Vpp). Then use probes to measure a capacitor and give the voltage drop in dB. A smaller number for a given capacitance makes you more suspicious that the capacitor has an ESR problem.

2542B-GEN function generator set to sine wave of 1 Vpp. The value measured by the 3456 was stored in the Y register (0.353420 V RMS) and this was used as a voltage reference for a dB measurement. The measured voltage drop of course is a negative dB value, but I'll report it here as positive. I used the GR resistance box to quantify the voltage drop. For each frequency, the function generator's output voltage was adjusted slightly (a few parts out of 1000) to read 0 dB with an open circuit.

	Voltage drop, dB				
R, Ω	**60 Hz**	**100 Hz**	**1 kHz**	**10 kHz**	**100 kHz**
1000	0.42	0.42	0.42	0.42	0.42
500	0.83	0.82	0.82	0.83	0.82
200	1.94	1.94	1.94	1.94	1.94
100	3.53	3.53	3.53	3.53	3.53
50	6.04	6.03	6.03	6.04	6.04
20	10.90	10.90	10.89	10.90	10.92
10	15.57	15.56	15.55	15.57	15.66
5	20.79	20.78	20.78	20.80	21.01
2	28.13	28.12	28.11	28.18	28.52
1	33.80	33.77	33.73	33.89	33.73
0.5	39.36	39.33	39.26	39.52	37.60
0.2	46.06	46.05	45.92	46.32	40.31
0.1	50.25	50.20	50.07	50.37	41.11
short	59.10	59.12	59.90	60.60	52.60

Here's a plot of these results:



The 100 kHz drop-off is possibly related to a frequency effect in the resistance box (and you'd expect the function generator to current limit). This is unlikely to be important, as most measurements using this voltmeter technique would probably be at 120 Hz or 1 kHz maximum.

100 nF mylar: 96.53 nF, 0.277 Ω BK886 at 100 kHz, 1 V. 10.4 dB drop via 3456; from graph, this interpolates to just under 20 Ω ESR. This is off by quite a bit.

300 μF electrolytic: 0.173 Ω ESR