I was deported from the USA!

If graphics on this page do not display correctly please read this.

Building an ESR meter for Testing Electrolytic Capacitors

Spanish

Brief introduction to electrolytic capacitors and ESR

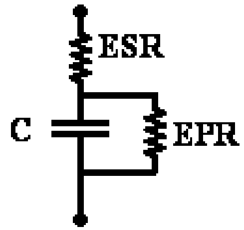
In repairing electronics in general and switch mode power supplies in particular I have noticed that electrolytic capacitors are very often the components that failed and caused the problem in the first place, even if that later made other components, often semiconductors, fail.

So, rather than trying to understand a circuit of which I most often do not even have a schematic, I find it a good approach to test all the electrolytic capacitors before I do anything else. Disconnecting all electrolytic capacitors from the board for this purpose would not be practical so we have to find a way of testing them in-circuit. Before we go any further in the testing process let us analyze and understand electrolytic capacitors a bit better.

An ideal capacitor only has capacitance but an actual, real world, capacitor exhibits, not only a pure capacitance but also has some inductances and resistances distributed. We will ignore the inductance and we will concentrate on the resistances which we will summarize in two: The Equivalent Series Resistance (ESR) and the Equivalent Parallel Resistance (EPR) as shown in figure 1. This simplified model is sufficient for our purposes.

The EPR causes a leakage current which heats the capacitor somewhat but this resistance is high enough that the leakage current is low enough. If this EPR decreases, the leakage current increases. This is not common fault in capacitors except when they short out and the

EPR drops to near zero.



The ESR also causes the capacitor to heat up as the ripple current charges and discharges the capacitor. The ESR parameter has become a more relevant spec in recent years due to physically smaller capacitors (which causes higher ESR) and higher ripple currents in switch mode power supplies.

Switched mode power supplies work at much higher frequencies than the mains and this means smaller capacitance values are required but this also means higher ESR values and more heating. Also, capacitors have become physically smaller over the years and this also means an increase in ESR. A capacitor which heats up tends to vent and dry up which leads to higher ESR. You see it soon becomes a chain reaction which destroys the capacitor.

Having understood all the previous concepts, we now want to test a capacitor. It would seem intuitive that the first thing we would want to measure is the capacitance value but this is not necessarily so because measuring the ESR can generally give us a better indication about the health of a capacitor and it is easier to measure in-circuit. As an electrolytic capacitor begins to dry up the ESR is affected much more than the capacitance. A capacitor with a correct capacitance value but abnormally high ESR is well on its way to failure because the high ESR will cause more heat which will end up destroying the capacitor. If the capacitor has already lost a fraction of its initial capacitance value, the ESR will normally have increased by a large factor.

The ESR of a good capacitor depends on many factors, capacitance value being maybe the most relevant. The higher the capacitance the lower the ESR. In any capacitor of over a few tens of uF it would be a fraction of ohm and even in the smallest electrolytic capacitors it would not be more than a few ohm. For a given capacitance the next most relevant factor is the quality of the design and manufacturing. Some capacitors are designed and built to have much lower ESR than others. After those two factors we have others which affect less like nominal voltage (for the same capacitor type/series, the higher the nominal voltage the higher the ESR) and temperature rating (the higher the temperature rating the higher the ESR). Purely as a general indication of what to expect I have built the following chart which gives the expected ESR in Ohms as a function of capacitance in uF and "quality" of the capacitor.

ESR in Ohms

	Quality				
C uF	Very high	High	Normal	Low	Very low

1.0	2.000	5.000	12.500	31.250	78.125
2.2	1.125	2.812	7.030	17.574	43.936
4.7	0.646	1.616	4.039	10.098	25.244
10	0.372	0.931	2.328	5.819	14.548
22	0.209	0.524	1.309	3.273	8.181
47	0.120	0.301	0.752	1.880	4.701
100	0.069	0.173	0.433	1.084	2.709
220	0.039	0.097	0.244	0.609	1.523
470	0.022	0.056	0.140	0.350	0.875
1000	0.013	0.032	0.081	0.202	0.504
2200	0.007	0.018	0.045	0.113	0.284
4700	0.004	0.010	0.026	0.065	0.163
10000	0.002	0.006	0.015	0.038	0.094

I have made that table with Excel to give values which are consistent with what I would expect off the top of my head. If you have more reliable values please let me know and I will update this chart. The formula I have developed and used in this chart is

$$\mathbf{ESR(Ohm) = 2 * 2.5^{\wedge Q} / C^{\wedge 0.73}}$$

where C is the capacitance in uF and Q is the "quality" rating of the capacitor with 0 being the best (negative would be even better) and with 4 being the worst (higher would be even worse).

Different applications require different quality levels. Everything else being equal, a power supply capacitor working at 50/60 Hz needs to have a capacitance 2000 times larger than one working at 100 KHz. A capacitor which is working at 100 KHz and is 2000 times smaller is going to have an ESR which is ten times greater and is going to generate much more heat in much less space. Miniaturization tends to increase ESR as well as impede heat dissipation. We can see everything here works against us. Whereas ESR is usually of no great concern in power supplies working at mains frequency it is a critical factor in switch mode power supplies (SMPS).

But when repairing SMPS we do not need exact ESR measurements and just a rough indication will do. So a very simple electrolytic capacitor test would be to measure the ESR roughly and consider the result to indicate good capacitor for, say, ESR<1 ohm, bad for ESR>10 ohm and in the range between 1 and 10 consider the capacitance and other factors. If it is a very small capacitor working with small ripple currents then maybe it is fine even with ESR of 5 ohm but if it is a large 1000 uF capacitor then it can be considered bad or, at least, requires further inspection.

As we see, we are more interested in a relative ballpark figure than in precise measurement. As soon as the ESR value starts increasing it generally spirals upwards quite fast so most of the time we can easily go quickly testing all the capacitors of a power supply and confirm them all as initially presumed good or detect one or several as obviously bad. This is a good way to start because, as I mentioned, electrolytic capacitors are so often at the root of the problem.

So, we need an ESR meter.

Building an inexpensive ESR meter

There are plenty of expensive ESR meters out there but we do not need that level of precision or expense. What we need is a cheap instrument we can carry around and which will give us approximate readings. I searched around for a good circuit to build myself and I ended up designing my own version based on several circuits I have seen and adding my own improvements.

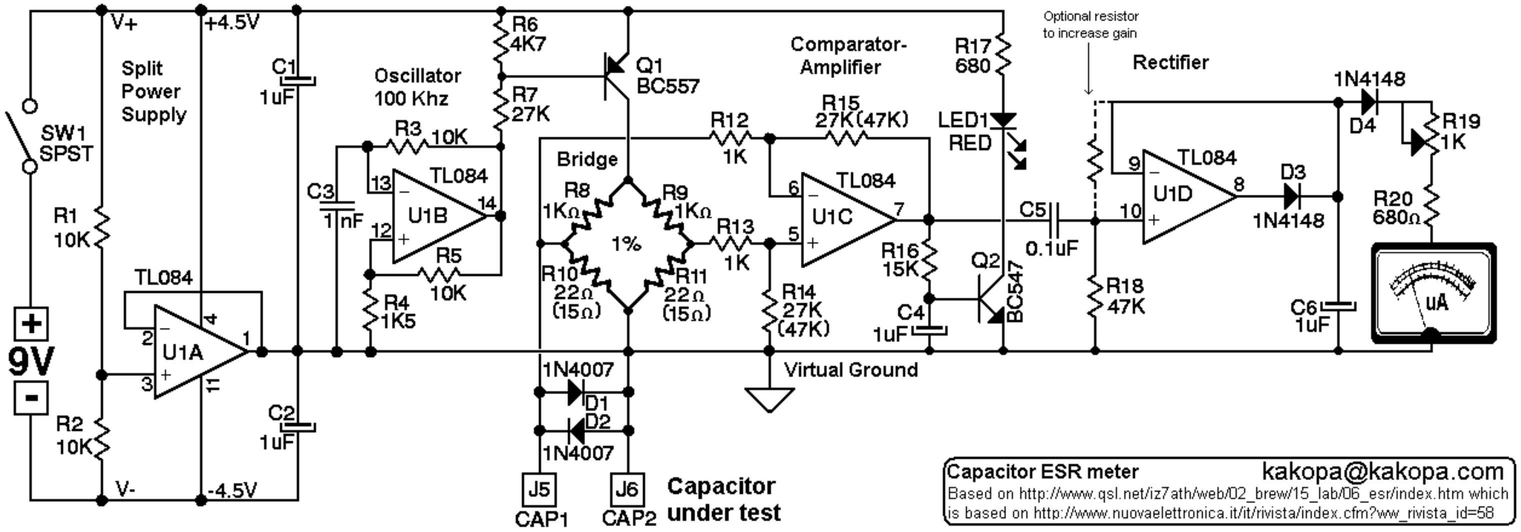
A feature I consider essential but most ESR meters do not have is an indication that the capacitor under test is shorted. A shorted capacitor will have an excellent ESR of close to zero but it is faulty and needs to be replaced. An ESR meter which only indicates ESR would indicate low ESR and, therefore, good capacitor. We need an indication that the capacitor is shorted.

Also, I want more precision in the lower part of the scale, say under 10 ohm, than in the upper because if the ESR value is over 10 ohm I am going to consider it a bad capacitor anyway. (When I say "lower" and "upper" I am referring to ESR ohm values as they are reversed in the galvanometer where the lowest ESR value makes the needle move the farthest.)

What follows is my own version of an ESR meter which I have built and works fine, although I am always improving my designs so I do not consider it final quite yet. But it works fine. It is based on this project by IZ7ATH which, in turn, is based on an article published as project #1518 by Italian magazine Nuova Elettronica, issue n° 212, dated Sept/Oct 2002. That, in turn, is a direct copy of the design published in Poptronics magazine in its July 2001 issue (page 25, credited to Marvin Smith, thank you Bud for sending it to me). I have made some changes to the circuit which I consider improvements.

The ESR meter has two test probes to connect it to the capacitor under test without removing it from the circuit. This injects a signal of about 100 KHz and under 100 mV(pp). This low level signal will not be enough to trigger semiconductors in parallel with the capacitor and most components one can expect would have higher resistance and would not interfere with the measurement.

The circuit is a bridge of four resistors which is normally balanced and the capacitor is placed in parallel with one of the legs which introduces an imbalance which is amplified by an op-amp. The lower the ESR, the greater the imbalance and the higher the reading.



Click to enlarge

Op-amp A, first from the left, divides the 9V power supply into two halves so we have +4.5 and -4.5 with respect to the center point which becomes our virtual ground. This symmetrical power supply is required by the op-amps which follow.

Second op-amp, B, is the basis for the 100 KHz oscillator. In practice I have noticed that the frequency tends to be not close to 100KHz, probably due to component tolerance values, so it is best to check it and trim the value of R3 to bring the frequency close to 100 KHz. While this is not essential, it permits better comparisons between units built. At the output of this op-amp we should have a square wave between -4 and +4 V pp.

The transistor which follows serves several purposes. It shifts the level of the signal so it is always positive, between 0 and +4 and it isolates the load that follows from the output of the op-amp which does not have a low enough output impedance to drive the bridge directly.

At the collector of the transistor we find the bridge which is the central part of the unit. The two upper resistors are much larger in value than the two lower ones so that the voltage which is put to the capacitor under test is a small fraction of the output of the transistor. Any imbalance in this bridge is amplified by the next op-amp, C. Let us analyze the different cases in detail.

Pin 7 of IC - Output of comparator op-amp.

Leads open - - - - - - connected to capacitor - - - - - - Leads shorted

1- When the leads are open, not connected to anything, the bridge is balanced and the output of the op-amp will be a constant zero volts.

2- When we connect a good capacitor we are shorting one branch of the bridge to ground **in AC** only, not in DC. Therefore the output will be an AC waveform with no DC component, i.e. it will be centered at 0 V and swing up and down from 0V.

3- When we further short the capacitor, then the branch of the bridge is shorted to ground in DC also and the output of the op-amp will be shifted upwards so that it has a positive DC component. Now the entire waveform will be above 0 V.

The difference is fed to op-amp C which amplifies it. The feedback resistors in the original were 47K but this led to a certain problem which was solved by lowering the gain by lowering the value of the resistors to 27 K. After building my prototype I am thinking that it may have been better to leave the 47 K resistors and lower the value of the two lower resistors of the bridge from 22 ohm to 15 ohm or even 12. That would make the instrument more sensitive to lower ESRs. I may try that in the future.

Several readers have reported the same problem so here is a more detailed explanation. What happens is that the meter shows lower ESR with a capacitor connected to the leads than with the leads shorted. The cause is that with the capacitor the wave is centered at 0 V but when the leads are shorted the waveform moves upward and this can lead to clipping of the upper peaks if there is insufficient power voltage headroom. Possible solutions may be to make sure there is enough voltage headroom or to lower the amplitude by lowering the gain. When seen on the scope the amplitude should be the same in both cases.

At the output of the op-amp we separate the AC and the DC components. First we see a low pass filter, composed by a resistor and capacitor, which allows the DC component to drive the base of the transistor which controls an LED. This LED will light if the capacitor under test is shorted or has high leakage current.

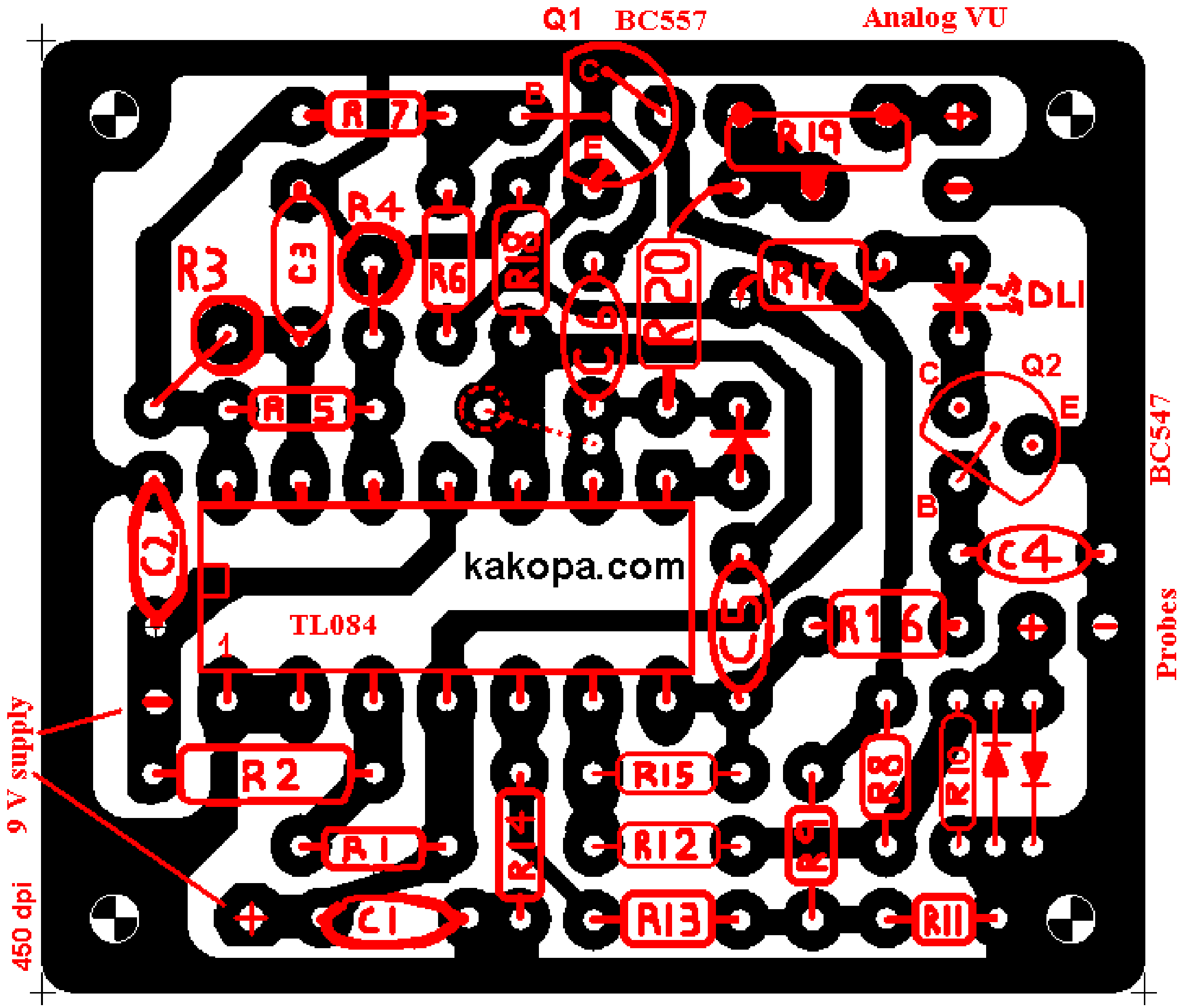
The AC is allowed through a high pass filter, formed by a capacitor (which blocks the DC component) and a resistor, into the input of the last op-amp D which is a rectifier. The lesser the ESR of the capacitor under test, the greater the rectified voltage will be. If the analog instrument needs more voltage then the optional resistor can be fitted which would increase gain. I adjust the circuit so that the maximum voltage out of the rectifier is about 1 volt. Then I have inserted a diode in series with the instrument. (This diode is shown in the schematic but not in the PCB because it was added after the PCB was designed and made. Just put it in series with R20.) The purpose of this diode is to expand the range of the instrument in the low ESR values and compress it in the higher ones. As the voltage rises, at first the needle hardly moves, but as the voltage passes 0.6 volts, the needle moves faster. This means the lower 0.6 volts hardly move the needle and the upper 0.4 volts are expanded to almost the entire range of the instrument.

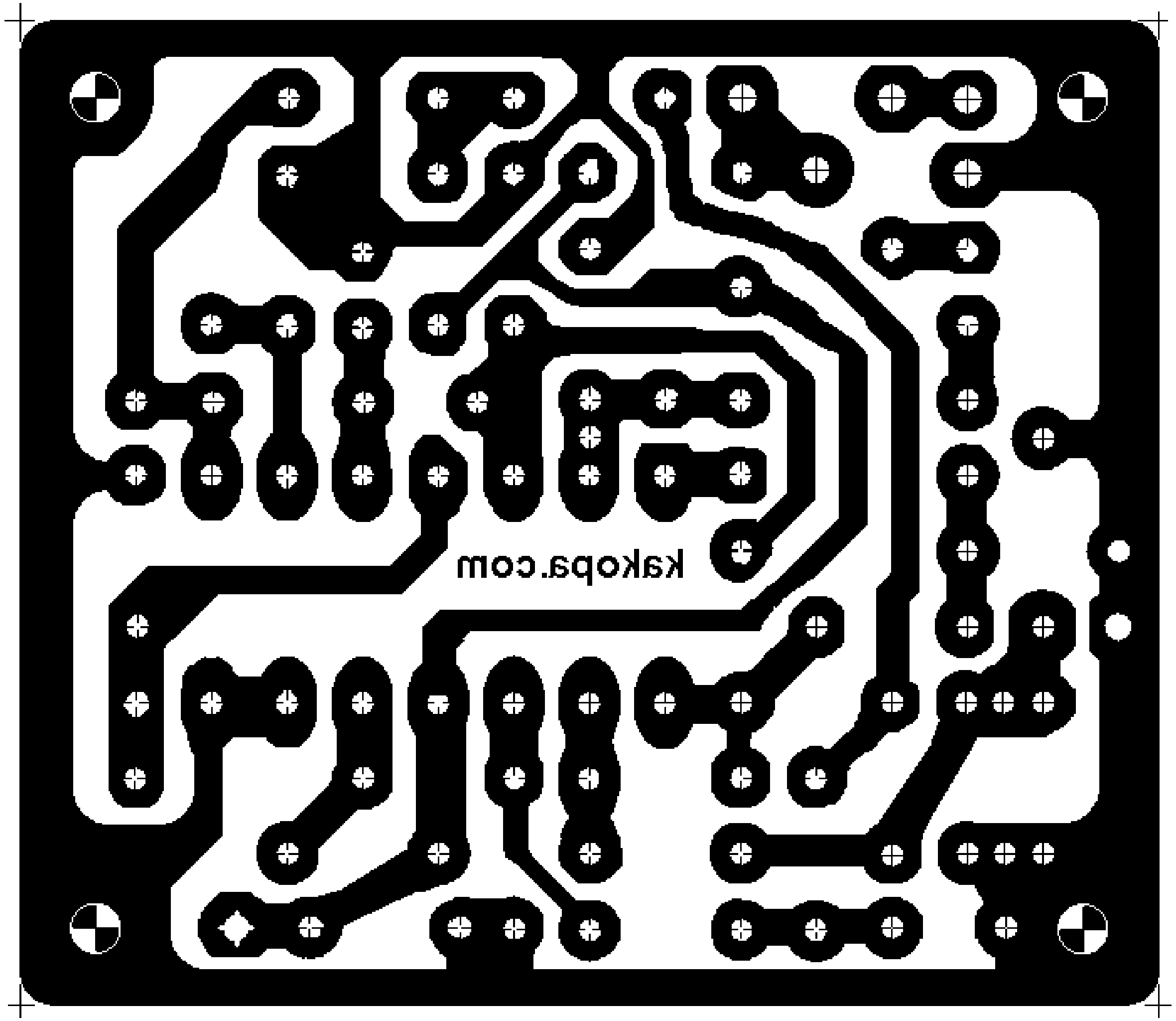
For the two 1 uF capacitors labeled C4 and C6 I have used electrolytic capacitors and they work just fine. I suppose if they had higher leakage current they would create problems but use tantalums and they should work just fine. I say this because in the original (Italian) design they are specified as polyester and some people complain they are huge and more difficult to find. In my experience electrolytics work just fine.

I have built a couple of prototypes using cheap galvanometers I had in my junk box. I have considered modifying the design to use a bar of LEDs but I decided not to do this for two main reasons. One is that a galvanometer can usually be found cheaper and gives more resolution than a bar of, say, 10 LEDs. Another is that a galvanometer will use much less battery power which is an important consideration when using 9 volt batteries.

I am still considering adding a circuit which will make the LED flash briefly at intervals as long as the instrument is turned on. This will remind us to switch it off and therefore save batteries.

Here is the PCB design. Note that, as I said, the design is not totally finished so there are discrepancies between the schematic diagram above, the names given to components (for instance, there is no TR1) and the PCB design. For example, R20 in the PCB has been replaced by a diode and resistor in series. Once I consider the design final, I will come back and clean everything up. . . . . . maybe. :-)





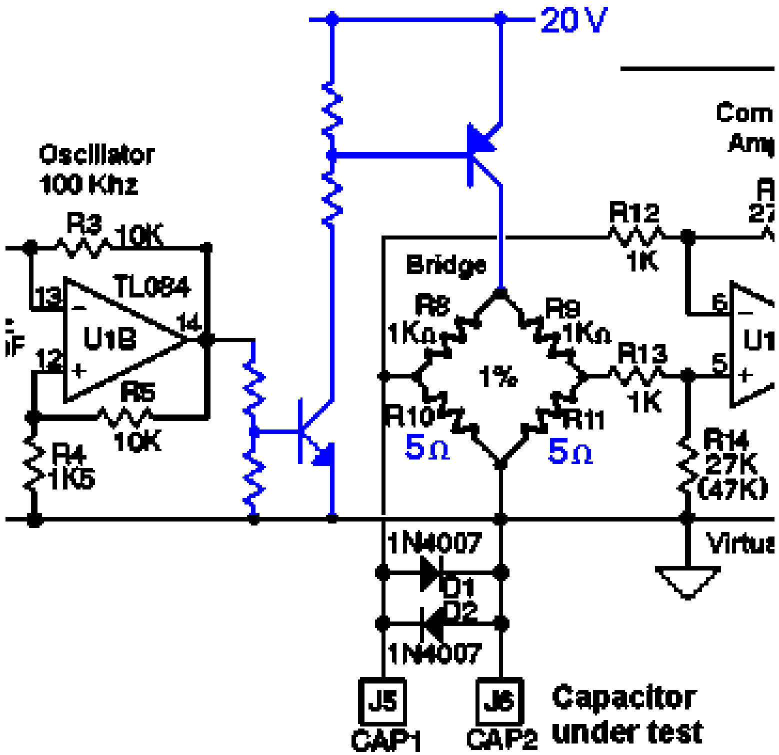
Here is a **link to a PCB layout** done by reader *capsighter*.

How to use the instrument

Turn the power switch on. Short the test leads and adjust R19 so the meter reads at end of scale. Connect leads to capacitor under test and read the meter. The closer the reading to end of scale the lower the ESR. The red LED should not light as if it does it indicates a shorted device. A reader of this page has made a short video showing how it is used. **Link**

Improving the sensitivity of the instrument

This page has become very popular and gets lots of visits. Some readers have emailed me asking if it is possible to increase the sensitivity of this instrument. To do that we need to decrease the equivalent output impedance at the testing leads. As I already mentioned earlier, one way to do this is to decrease the value of R10 and R11 and increase the gain of the comparator-amplifier circuit which follows. I suppose some sensitivity can be gained this way but there is a limit to how much because too much amplification would cause noise to be picked up and amplified. A way around this problem would be to lower R10 and R11 and to increase the voltage to the bridge proportionally so that the voltage at the testing leads remains the same. The rest of the circuit would remain exactly the same and fed at 4.5 V but the bridge would be fed at, say, 20 V. Here's the basic idea:



An extra transistor needs to be added to do the voltage shift between the output of the oscillator and the new, higher supply voltage. I have chosen 5 Ohm and 20 V as an example but sensitivity could be increased further by using 1 Ohm and 100 V. You need to make sure all the components involved are correctly dimensioned; the transistors have to bear the increased voltage and the 1 K resistors have to dissipate more power.

Conceptually this is a very simple way of increasing sensitivity while maintaining the basic concept of the circuit but it complicates the power supply as we now need a new supply voltage. Still it may be acceptable in a mains supplied lab instrument which is not considered portable. On the other hand it might be worth redesigning the entire circuit so that it would work with $^+$/-15 V or $^+$/-20 V instead of $^+$/-4.5 V. This would require either a mains power supply or a switching circuit which would produce the higher voltages from lower voltage cells.

One way to increase the bridge voltage *a little bit* without making major changes to the circuit would be to divide the 9 V of the power supply unequally by changing the ratio R1 / R2. The circuit needs more headroom in the upper half than in the lower half so we could divide the 9V into 3.5 + 5.5 V or even 3.0 + 6.0 V. I think that would work but I have not tried it.

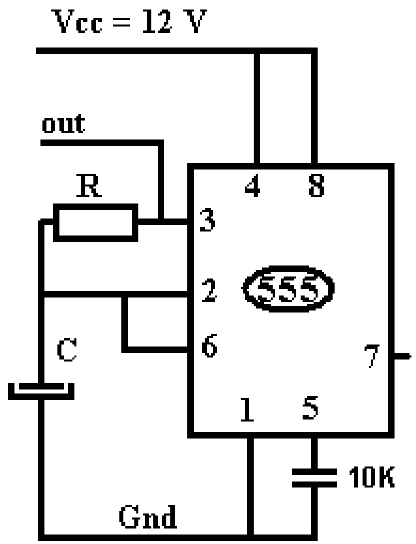
Another way to lower the impedance at the test leads is to use a transformer and this is what most circuits do. Many people have a problem with winding transformers though and prefer a circuit which only requires parts which are easily obtainable. An additional problem with using a transformer is that it would block the DC component which detects if the capacitor is shorted. Most ESR meters do not have this feature but I think it is quite useful so I would want to keep it. From my junk box of components I have already selected a transformer which is suitable for an ESR meter and one day I will design an ESR meter with this transformer. But, as I said, many people dislike building a circuit which requires special transformers.

Building an inexpensive Capacitance meter

I have devised a simple way to test their capacitance although it requires removing the capacitor from the circuit.

It is as simple as a 555 astable oscillator where the period of oscillation is proportional to the value of the capacitance. I then use my period/frequency meter to display the period of the oscillation. Using the correct resistance value I have found the period in milliseconds equals the capacitance value in uF which makes it easy to use. I have no idea how precise it may be as I do not have high precision capacitors to calibrate it with but it is good enough for quick and dirty work where you just want to check if a capacitor is good or bad. Electrolytic capacitor used in power supplies are not critical in value and have high tolerances anyway. We just want to check if a capacitor is reasonably within its intended range.

The circuit cannot be simpler and I have found that using R=560 ohm gives me a reading of T = 1ms/uF which is quite convenient. I have used it for caps in the 1 to 1000 uF range and it works well. If your frequency meter cannot display period duration, I guess you could count frequency and calculate the inverse but this would be slow as the frequency is so slow.



I have noticed that of two caps of equal nominal capacitance value but different voltages, when tested at the same value, the one with higher rated voltage will display a lower capacitance. For instance, of two caps of equal indicated capacitance the one rated at 16 V will display 20% less capacitance than the one rated 10 volts. So don't think that using higher rated voltage capacitors comes at no cost

Also note that caps rated at higher temperature and/or higher voltage will have higher ESR.

This page modified
2015-07-02. Added link to pcb layout by capsighter.

2014-03-29. Added paragraph with explanation of problem caused by waveform clipping.

2012-02-08. Added *"How to use"* section and link to Youtube video.

2010-03-19. Added section "Improving the sensitivity of the instrument".
Also added the 'scope trace image of the output of the comparator-amplifier.
I am pleasantly surprised at the large number of visits this page is getting lately.
In one of my visits to China I might look into the possibility of having a number of these ESR meters manufactured for me and selling them online.

2009-10-21. Added table with ESR values as function of uF

kakopa@kakopa.com