# Capacitor ESR Tester

## the good, the bad and the leaky…

Design by Flemming Jensen

How about an in-circuit capacitor tester to take the strain out of tracking down faulty capacitors? No need to solder out any capacitor, simply check it in-circuit, from thousands of microFarads down to a hundred nanoFarads. In most cases, parallel coils or low value resistors are no problem. Even shorted caps may be revealed in-circuit and polarity is irrelevant for the tester. High ESR? Replace!


The most significant property of a capacitor is its capacitance but besides that there's another important factor, namely the so called **ESR**, or Equivalent Series Resistance. An ideal capacitor is a purely reactive component with a 90-degree phase angle between current and voltage. In the real world, however, a capacitor needs to be modelled as an ideal capacitor in series with a resistor representing the losses introduced by the component. The equivalent circuit is shown in **Figure 1**. Sure, capacitance can be measured by means of a capacitance meter, which is pretty common nowadays, but unfortunately this test won't tell anything about the capacitor's quality — we need to know the ESR as well. Over time, electrolytics tend to dry out, which will raise their ESR and inevitably the voltage drop inside the capacitor. Evidently, the pure reactance $X_C$ can not produce heat, due to the 90-degree phase shift between voltage and current, but the ESR can, and in switching circuits the resultant heat will cause a further degradation of the capacitor's quality i.e., a further rise in ESR. It's fairly common to find electrolytics that on the face of it have only lost just a few

## How does ESR influence circuit behaviour?

In (fast) switching circuits, a low ESR may be crucial for proper circuit behaviour. For example, in a TV set, high capacitor-ESR may lead to inability to quit stand-by mode, incorrect picture height or width, synchronisation problems, interference or hum bars. In Switch Mode Power (SMPSUs) supplies, high ESR caps may lead to blown semiconductors, blown fuses or no start up. In power circuits, a rising ESR will make the capacitor warm up, leading to even higher ESR and eventually circuit breakdown. The usual method to troubleshoot these problems involves soldering out the capacitors, measure the capacitance and solder the good ones back in. A tedious task, but what's even worse, ailing capacitors often don't show a low capacitance, get soldered back in again and then the troubleshooting gets really time consuming.

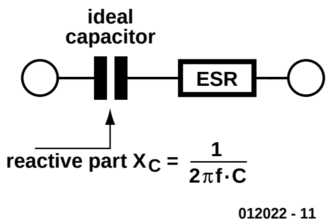



Figure 1. The most important property of a capacitor is its capacitance but beside that there's another important factor, namely the so-called ESR, or Equivalent Series Resistance.

percent of their rated capacity although their ESR is in the hundred Ohms range. Obviously, such a component acts as a load just running hot and wasting a lot of energy.

### The measuring principle

The capacitor under test, C.U.T., is fed with a 100-kHz constant-current square wave signal. The ESR value is determined by measuring the AC voltage drop across the C.U.T. If the capacitance is high enough compared to the frequency, the voltage drop over the internal reactance is negligible and the drop is caused by the ESR only. This voltage is converted to DC and fed to the voltmeter section.

AC to DC conversion of a 100-kHz signal in the millivolts range presents a real design challenge. Furthermore, the conversion needs to be as linear as possible because we want to use an ordinary 200-mV DVM readout. It goes without saying that an ordinary diode rectifier will not suffice, and an active diode rectifier with opamps will have a hard time working at 100-kHz and a few millivolts. The solution we came up with is a **synchronous rectifier** — essentially a polarity changer controlled by the same generator that supplies the 100-kHz test signal. This circuit works surprisingly well and is cheap, too!

A simplified version of the circuit is shown in Figure 2. Here, the C.U.T. is assumed to be a 100-µF with an ESR of 10 Ω. As shown, the reactance is negligible and the ESR, which is purely resistive, is dominating.

Although the above principle works well, further reduction of the reactive influence is called for.

**Figure 3** shows an example where the C.U.T. is 0.1-µF cap whose ESR is zero Ohms. As mentioned above we use a relatively high frequency to make the reactance negligible while enabling even the smallest electrolytics like 0.1-µF to be tested. For this it is necessary to reduce the influence of the beginning integration of the waveform even further. The ESR is zero and the reactance is 15 Ω. As can be seen, the integrated waveforms presented to the differential amplifier inputs result in a sawtooth centred around zero volts at the output. After integration, in the RC network that follows, a DC level of zero volts is fed to the voltmeter circuit. If the C.U.T. also represents an ESR of, say, 10 Ω, the sawtooth at the output will still have the same waveform. However, it will be DC-shifted in the positive direction by an amount representing

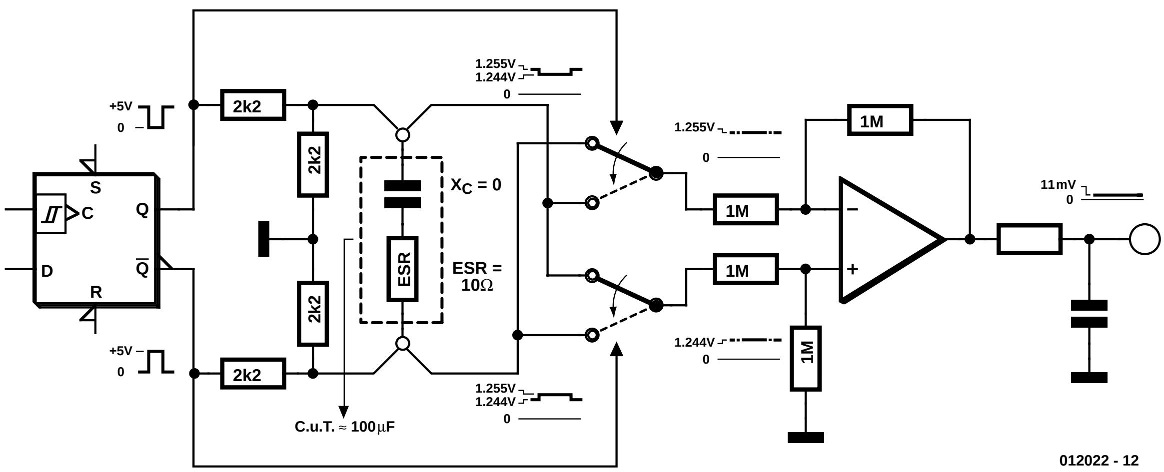



Figure 2. Illustrating the principle of operation. Assuming that the C.U.T. is a 100 µF capacitor with an ESR of 10 Ohms, the reactance is negligible and the ESR, which is pure Ohmic, is dominating.

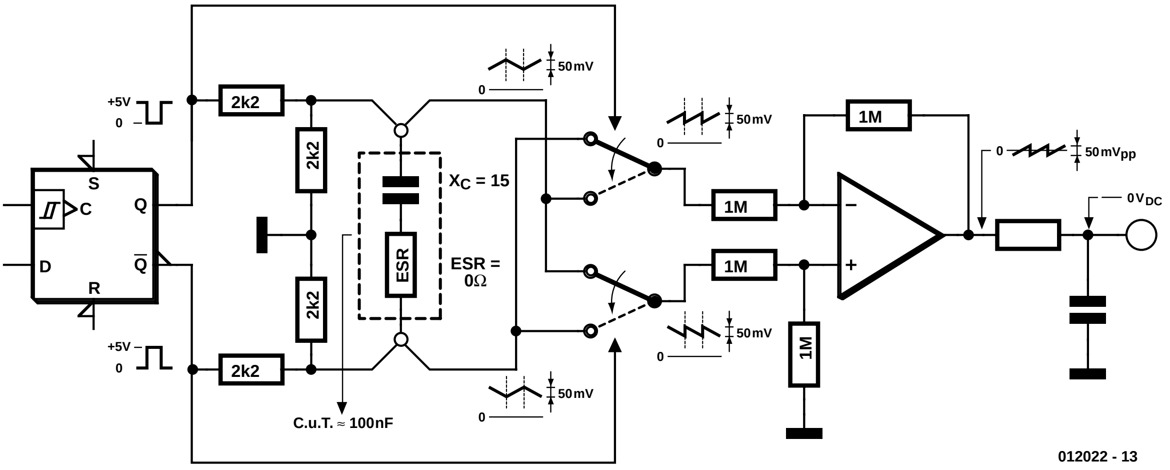



Figure 3. Second hypothetical test: C.U.T. is a 0.1-µF capacitor with an ESR of 0 Ω.

the ESR value. After integrating the sawtooth away, the output will give the proper reading of 10 Ω, excluding the 15 Ω reactance.

## Low-ESR cap or shorted cap?

You may question if you're testing a low-ESR cap or simply a shorted one. A simple DC Ohms test is usually enough to decide this. No need to get out the multimeter — with a push of a button the ESR tester becomes a DC Ohmmeter and your display should change to a higher Ohm reading. If it doesn't, the odds are you have a shorted cap on your hands.

## Some practical ESR values, please?

So how high will the ESR be then? Well, that depends on where the capacitor is used, the type, the make, the voltage rating, etc. A 2,200-µF reservoir capacitor with an ESR of 10 Ω may be fine in a linear power supply, while a 2,200-µF one having 1 Ω ESR may be grossly inadequate in a switch-mode PSU.

In general, if a large capacitor, as in this example, reads more than one Ohm, you should be suspicious and run a comparison on a similar component. But don't worry! It won't take long before you are able to distinguish bad caps from good ones. If you regularly are repairing SMPSUs, TV sets, monitors etc. you will soon appreciate the ESR tester.

## Circuit diagram

Let's have a look at the circuit diagram of the Capacitor ESR Tester — see **Figure 4**. A 200-kHz square wave generator is built around IC1. This signal is divided in IC2.A which in fact constitutes our bipolar 100-KHz test signal generator. Series resistors R6 and R3-P3 on the Q and $\overline{Q}$ outputs of IC2.A give the generator a high output resistance compared to the low ESR, and, essentially, make the generator act as a 100-kHz, balanced, constant-current generator. The voltage drop across the C.U.T. is taken to IC3, four bilateral switches coupled as a controlled polarity changer, changing polarity in sympathy with the outputs of IC2.A. This enables IC3 to act as a (rudimentary) ADC. IC4.A, a differential amplifier, converts the differential signal into a single-ended signal, i.e., one which is referenced to ground. IC4.B amplifies the signal such that it can be applied to a 200-mV voltmeter. IC9 is the voltmeter IC, here the ICL7106 is used with an LCD, all in a standard configuration. The LM358 in position IC8 is a comparator that tells you when it's time to change the battery. IC7, finally, generates the negative supply rail for the circuit.

As shown in the circuit diagram, the test probes carry two screened wires each. Each probe carries a signal wire (e.g., 'A') and a measuring wire (e.g., 'B'). More about the probes under 'Construction'.

## Construction

A compact printed circuit board was designed for the Capacitor ESR Tester by the Elektor labs. The resulting double-sided through-plated board design is shown in **Figure 5**. As appropriate for a test instrument, the board is designed such that all adjustment points are easily accessible, in this case, from the sides of the board (multiturn presets P1, P2, P4, P5) and from the top (preset P3).

Although the construction of the board follows standard practice (of which the main maxim is: *work carefully*), a few things should not be left unmentioned. Firstly, the circuit board has a screening ground plane at the component side, so care should be taken to avoid short-circuits by solder blobs or solder hairs between component terminals and the ground plane. Secondly, ascertain, check and double-check the polarity of any polarized component, in particular the tantalum capacitors in positions C3, C4 and C5. Tantalum capacitors when reverse polarised have a nasty habit of exploding and emitting hideous fumes. Finally, we recommend using sockets for all ICs (except IC9) and the LCD. The latter is easily made by cutting a 40-pin IC socket in two (lengthwise) and using the two 20-way socket strips.

Small holes should be drilled in the two long sides of the ABS case to allow P1, P2, P4 and P5 to be adjusted from the outside.

Regarding the probes, their basic construction is illustrated in **Figure 6**. These two wires are soldered together as close to the probe tip as possible. In this way the voltage

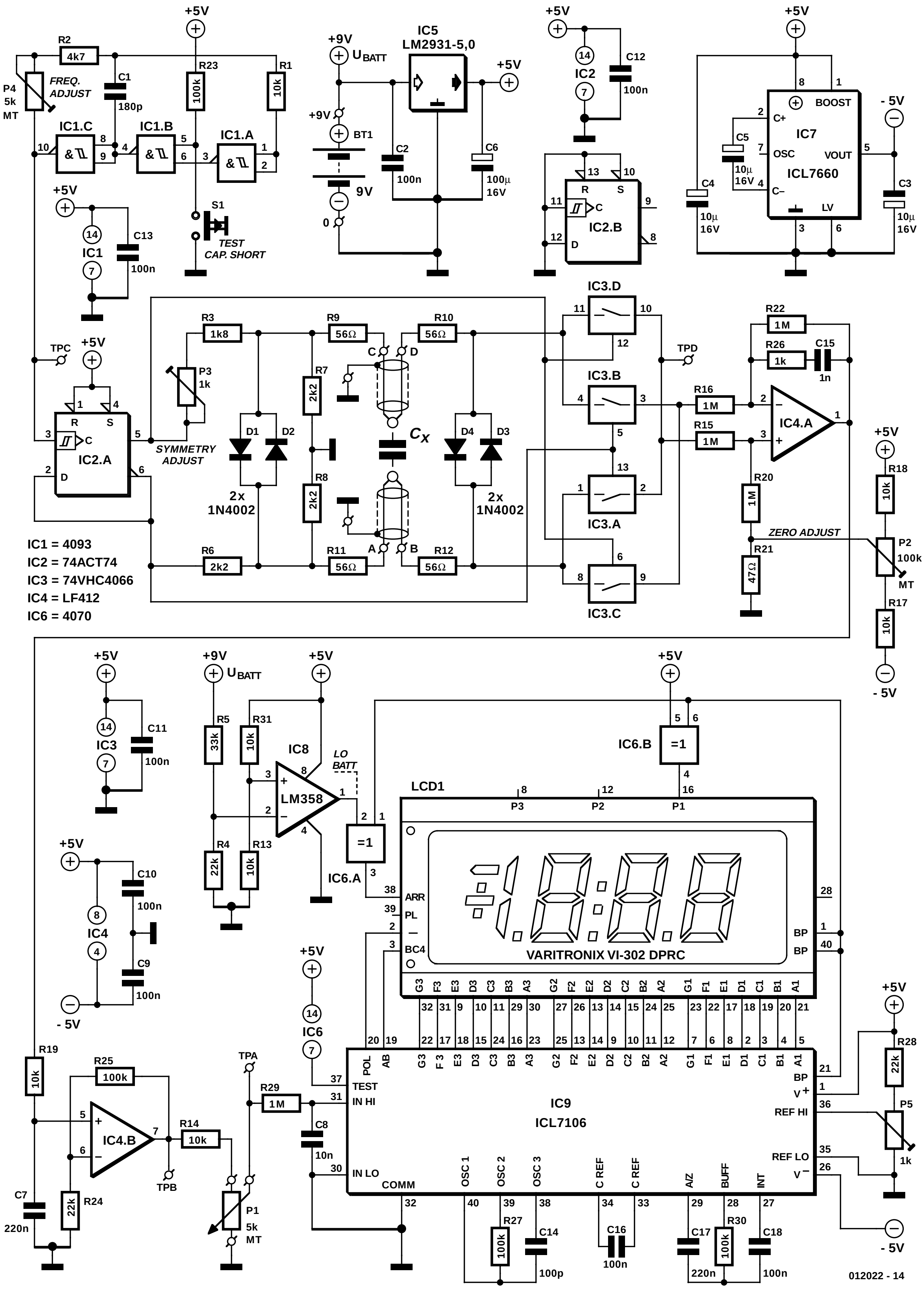
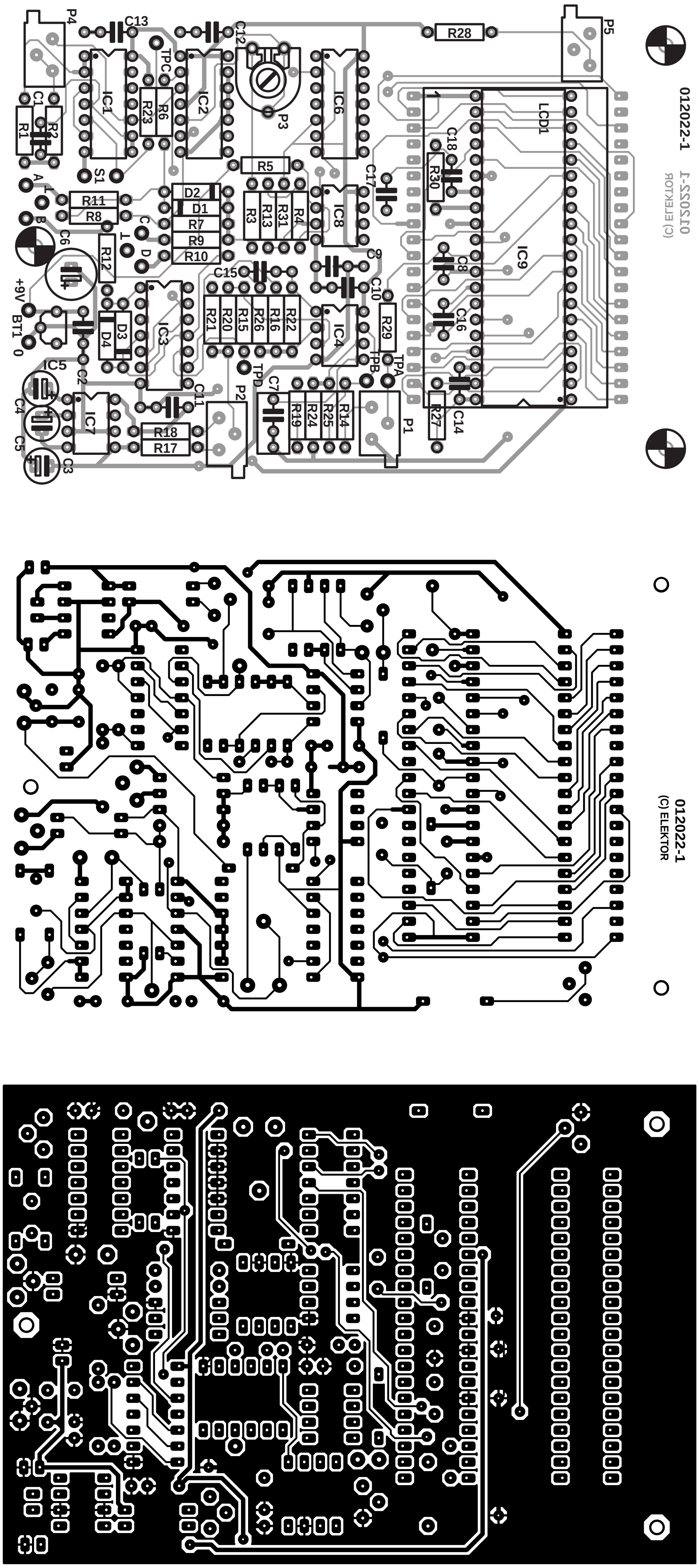


Figure 4. Circuit diagram of the Capacitor ESR Tester. $C_x$ is the capacitor under test.



drop along the signal wire will not add to the measurement. The screening ensures that the test leads do not pick up noise, and that you maintain a stable zero adjustment.

## The ESR Tester as an add-on

The most costly parts in the circuit are the display and the 7106 A-D converter. Money can be saved if you decide to use the ESR Tester as an add-on for an existing digital multimeter (DMM). Switch the multimeter's range selector to the 200.0 mV/DC position and connect the inputs to GND and the wiper of P1. You should not be tempted to supply the ESR Tester from the multimeter's battery. Remember, the ESR Tester has its output referenced to ground, so if you run it off the multimeter's battery the Tester will have its battery minus connected to the input common terminal, which is far from advisable. Use a separate battery for the ESR Tester to avoid any problems. Or if you really want to use just one battery, give the ESR Tester an add-on 9-volt battery, connecting the ESR Tester's regulated plus 5 volt to the plus terminal of the multimeter's battery connector and the ESR Tester's minus 5 volts to the multimeter's minus terminal.

## A few words of warning

Though the ESR Tester has diode-protected inputs, it is still a good idea to discharge any largish capacitors you want to test. Some reservoir capacitors in power circuits contain so much energy that the protection circuit may burn out. If this should happen, the defective components are usually to be found in the protection circuit alone. The remedy should therefore be pretty straightforward and inexpensive.

Figure 5. Copper track layout and component mounting plan of the PCB designed for the instrument. Double-sided, through-plated board, available ready-made (see Readers Services).

## COMPONENTS LIST

**Resistors:**
R1,R13,R14,R17,R18,R19, R31 = 10kΩ
R2 = 4kΩ7
R3 = 1kΩ8
R4,R24,R28 = 22kΩ
R5 = 33kΩ
R6,R7,R8 = 2kΩ2
R9-R12 = 56Ω
R15,R16,R20,R22,R29 = 1MΩ
R21 = 47Ω
R23,R25,R27,R30 = 100kΩ
R26 = 1kΩ
P1,P4 = 5kΩ multiturn preset, vertical mounting, side adjust (Bourns 3266X, Farnell #347-747)
P2 = 100kΩ multiturn preset, vertical mounting, side adjust (Bourns 3266X, Farnell #347-784)
P5 = 1kΩ multiturn preset, vertical mounting, side adjust (Bourns 3266X, Farnell #347-723)
P3 = 1kΩ preset, horizontal mounting

**Capacitors:**
C1 = 180pF
C2,C9-C13,C16,C18 = 100nF
C3,C4,C5 = 10μF 10V radial
C6 = 100μF 16V radial
C7 = 220nF
C8 = 10nF
C14=100pF
C15 = 1nF
C17 = 220nF

**Semiconductors:**
D1-D4 = 1N4002
IC1 = 4093
IC2 = 74ACT74 PC
IC3 = 74VHC4066
IC4 = LF412-CN
IC5 = LM2931-5,0
IC6 = 4070
IC7 = ICL7660
IC8 = LM358-N
IC9 = ICL7106-CP

**Miscellaneous:**
LCD1 = 3.5 Digit LCD with LO-BATT indicator, e.g., Varitronix VI-302 DPRC (Farnell #478-660)
S1 = pushbutton, 1 make contact
Battery holder
On/off switch
2 miniature probes, e.g., Hirschmann PRUF1 (Farnell #523-483)
Length of 2-core screened cable
ABS enclosure with LCD window and battery compartment, e.g. Multicomp type BC4, (Farnell # 645-758)
40-pin IC socket cut in half (see text)
PCB, order code 012022-1, see Readers service page or www.elektor-electronics.co.uk

## ESR Tester adjustment

Before adjusting the instrument, be sure that you have a regulated plus 5 V from IC5 and minus 5 V from IC7. If you don't, you'll have to troubleshoot your circuit board.

1. Start with the voltmeter circuit. P1 should be disconnected at this point. Connect a known, accurate voltage source of less than 200 mV to point TPA (test point A) and adjust P5 until the LCD shows the right value. Remove the voltage source. Connect TPA to TPB, short the test leads together, and adjust P2 for a '000.0' reading. Remove the connection. Reconnect P1.

2. Connect a frequency counter or an oscilloscope between TPC and GND. Adjust P4 for 200 kHz counter reading or 5 µS period time on the oscilloscope.

Connect the test leads to a 10-Ohm resistor. Connect an oscilloscope (in AC mode) between point TPD and GND. Turn P3 (symmetry adjust) so that the two half cycles line up and produce a straight line. Adjust P1 for a '10.0' DVM reading.

If you do not have a counter or a 'scope available, turn P3 and P1 to the centre of their travel.

To ensure that the ESR Tester works properly you can connect different (known, good) capacitors in series with different resistors and have these simulate capacitor ESR.

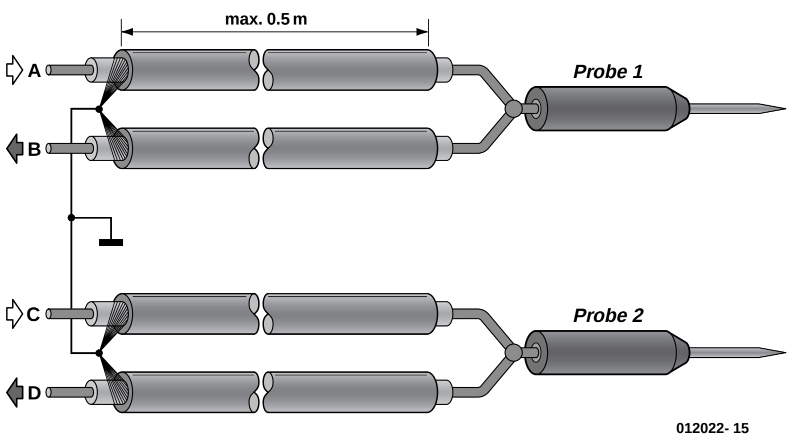



Figure 6. Here's how to make the 4-wire test leads between the probes and the instrument proper.

## Component considerations

The LF412 in position IC4 is a good choice for the differential amplifier. Since we are dealing with high frequency signals in the millivolts range, low drift, low offset and high bandwidth are crucial. Many different op-amps have been tested but most resulted in DC drift problems. The LF412 emerged as a good, low cost choice causing minimal drift.

IC5, then, is a 5-volt regulator that works just fine at a voltage drop less than 600 mV and so ensures long battery life. This regulator enables the circuit to keep working down to a battery voltage of less than 6 V. IC2, a 74ACT74, is capable of delivering enough current at 100 kHz to produce a nice clean square wave. IC3 is a high speed (VHC) version of the well known 4066. Compared to the common 4066, the effect of unwanted reactance is halved. For best performance the specified components should be used, but all in all, quite acceptable performance is achieved still if you use an ordinary 4066 for IC3, and a 74HCT74 for IC2.

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## Related websites:

www.awiz.com/cwinfo.htm
www.flippers.com/esrkttxt.html