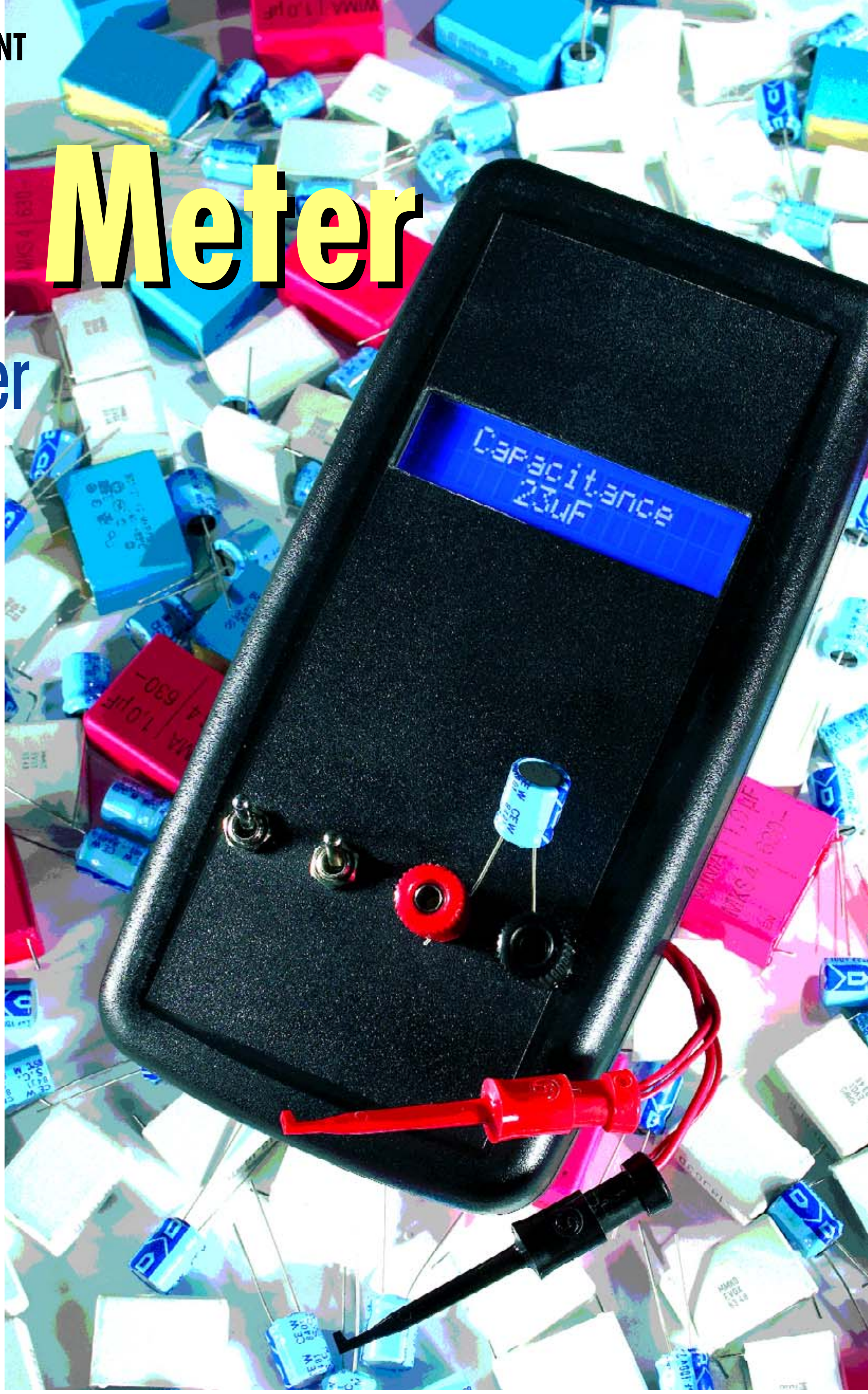
ESR/C Meter

A versatile meter for capacitors



Flemming Jensen

The two most important properties of a capacitor are its capacitance and its internal resistance (ESR). You need to know both values in order to judge whether a capacitor is suitable for a particular application. The meter described here combines two popular *Elektor Electronics* projects to create a convenient new instruments that rightly belongs in every well-equipped electronics lab.

Digital capacitance meters have become fairly inexpensive. Most commercial capacitance meters have a measurement range of a few picofarads to 2,000 mF. Some can even go as far as 20 mF, but that's where it stops. Large capacitors with values of several hundred millifarads, which are often used in power supplies, printers and photocopiers, cannot be measured using such meters. That means you will need a different (and more advanced) type of meter.

There's another important property of a capacitor that cannot be measured using a normal capacitance meter: its equivalent series resistance (ESR). Beside the capacitance, it is one of the most important properties of a capacitor. An ideal capacitor is a purely reactive component, with a 90-degree phase shift between voltage and current. However, practical capacitors also have a non-zero resistance in series with the 'ideal' capacitance (see **Figure 1**). The resistance represents the losses inside the component, and it largely corresponds to the quality of the capacitor.

Electrolytic capacitors tend to dry out after a long time, which causes their ESR to increase. A pure reactance cannot generate any heat, due to the phase shift of exactly 90 degrees between voltage and current, but a resistance can generate heat. The heat dissipated in a capacitor due to its ESR increases in a switch-mode circuit, which causes its quality to deteriorate even more. With an aged electrolytic capacitor, it is not uncommon to find that although the capacitance has decreased by only a few percent, the ESR is more than 100 Ω. An ESR of this magnitude makes a capacitor completely unusable in switch-mode circuits and hardly usable for any other type of application.

Why a combined meter?

An ESR meter and a capacitance meter measure two different things. They complement each other. That's why it's convenient to combine the two measurements in a single instrument. For this purpose, the author has merged the especially popular ESR Tester published in the September 2002 issue with the Autoranging Capacitance Meter published in February 2003 (and also designed by the author). The result is a handy instrument with a dual function and outstanding characteristics.

The new instrument also has a considerably more up-to-date design than the original versions. The design of the original ESR meter was based on a voltmeter IC, but new design is built around a type 16F877 PIC microcontroller. The advantage of this is that some new features can be added, while there is also enough room for the program for the capacitance meter.

The following capabilities have been added to the ESR meter:

- AC resistance (ESR) and DC resistance are displayed simultaneously. In the old design, you had to select one or the other by pressing a switch. The DC resistance indicates whether the capacitor is internally shorted (and thus simply 'kaput').
- The new design asks the user to short the probes together when the meter is switched on, so the offset can be measured. With the old design, this had to be handled mechanically.
- An audio function is built in to avoid having to always keep an eye on the meter. That's primarily helpful when you're making measurements on capacitors deep inside a device. The rounded-off ESR value is indicated by beeps. If the measured ESR is in the range of 3.1–4.1 Ω, for instance, four beeps are emitted. The meter also generates a warning signal if the DC resistance is less than 10 Ω. No beeps are emitted if the measured ESR is greater than 10 Ω, since a capacitor with such a high ESR value probably should be replaced. If no signal is emitted, you should briefly check the display to see what's wrong.

No new functions have been added to the capacitance meter. Here the major change consists of rewriting the code for the PIC16F877.

Measurement principle of the capacitance meter

The complete schematic diagram is shown in **Figure 2**. The circuit of the capacitance meter is based on a CMOS version of the well-known 555 timer IC, which is used here as a monostable multivibrator. The PIC provides the reset signal, controls the trigger input, and monitors the output of the 555. The larger the value of the capacitor to be measured, the longer the output of the 555 remains high. A counter in the PIC counts up as long as the output remains high. The count is read when the output goes low.

The PIC automatically switches between the various measurement ranges. The meter has three ranges: 1–9999 pF, 10–9999 nF, and >10 µF. To make the measurement easy to read, a value of 1000 pF or 1000 nF is shown as 1.00 nF or 1.00 µF, respectively.

The capacitance meter has automatic zero adjustment. After the instrument is switched on, the PIC executes a routine to measure the residual capacitance of the probe leads or other external circuitry. The measured value is subsequently subtracted from every reading to yield the correct value, so the offset resulting from using different probe leads does not affect the reading. It's thus important to ensure that the meter is not connected to a capacitor when it is switched on, although this actually only applies to the picofarad range.

For capacitance measurements in the other ranges, no problem will result if the capacitor is already connected before the meter is switched on. Immediately after the automatic zero adjustment, the meter starts measuring in the picofarad range. If the capacitance is too large, a counter overflow occurs and the PIC selects the nanofarad range. A lower charging resistance is selected for this range (R17–R19 and P2–P4), so the charging current is higher. If the capacitance is still too large, the PIC switches to the microfarad range and completes the measurement in that range, regardless of the charging time. The results are displayed on a two-line alphanumeric LCD module.

Hum interference

The input impedance is very high in the picofarad range. In that range, the capacitor is charged via a resistance of 5–6 MΩ. As a result, the meter is quite sensitive to AC mains interference (hum) in the picofarad range. You should keep the meter well away from transformers and similar components when making measurements in the picofarad range, since otherwise the displayed value may fluctuate.

In order to suppress the effects of possible hum, the measurement is made twice in the picofarad range at an interval of 10 ms. The average value of the two measurements is calculated and displayed. That makes the measured value more stable. The impedance is relatively low in the two other ranges, so no special measures are taken. The measurements on those ranges are thus single measurements without any averaging.

Large capacitances

Capacitors with values less than 10 mF are continuously measured. The measurement cycle is repeated periodically starting with the picofarad range, followed by the nanofarad range and then the microfarad range. Capacitors with values greater than

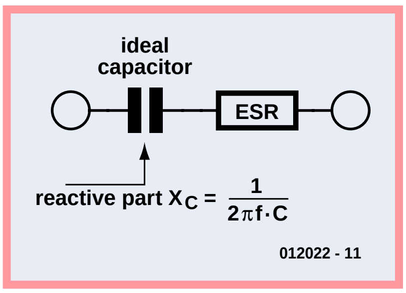


Figure 1. The most important property of a capacitor is its capacitance. The second most important property is its equivalent series resistance (ESR).

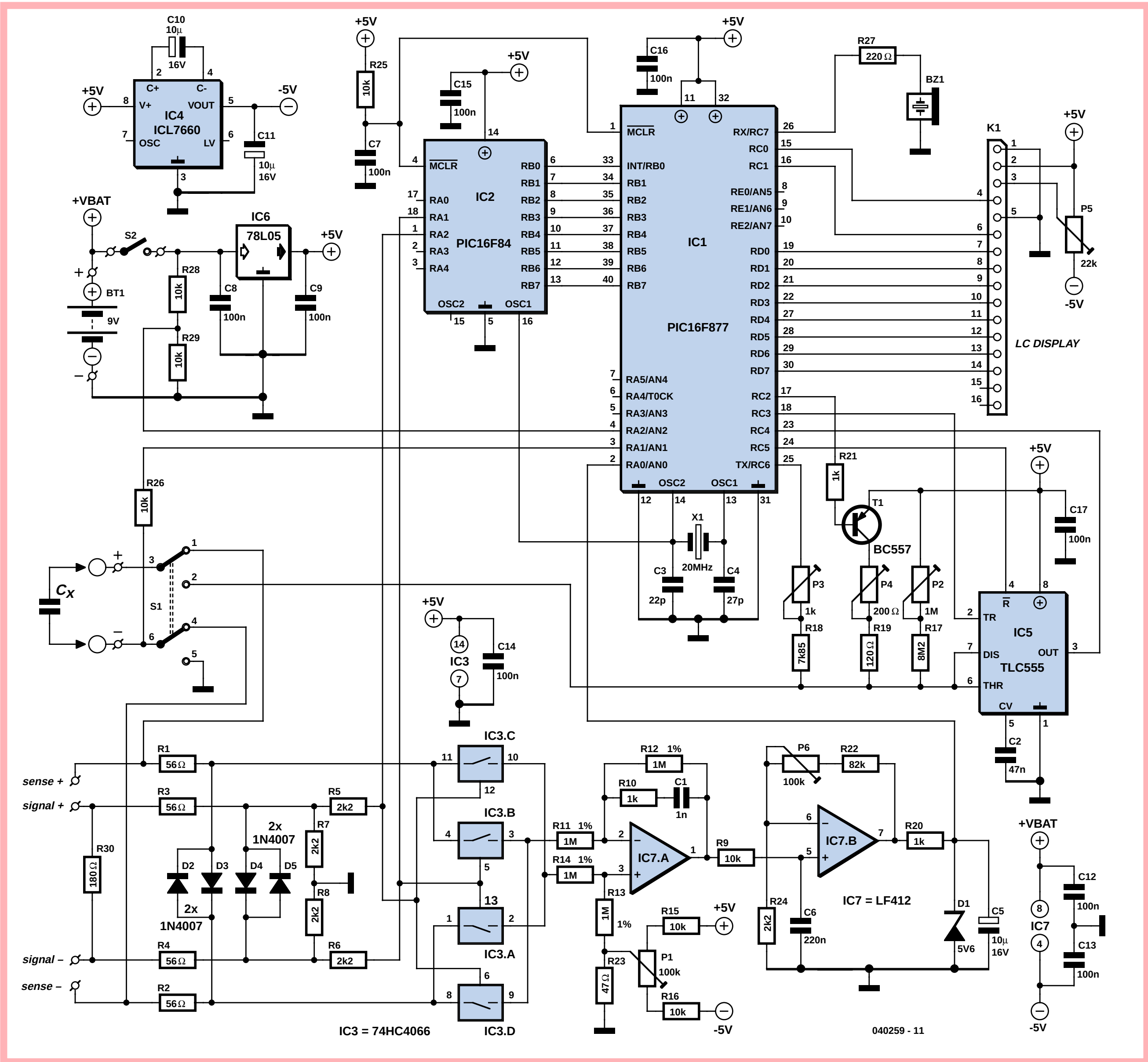


Figure 2. The complete schematic diagram of the capacitance/ESR meter.

10 mF (milli-farad) are not measured continuously. Instead, a series of four measurements are made and the results are then averaged.

This method ensures that the capacitor is fully discharged and charged and generates highly reliable measurements. It also limits the current consumption. The instrument must be switched off and then on again in order to make a new measurement. Continuous measurements are made in all other ranges.

Measurement principle of the ESR meter

A 100-kHz square-wave signal that supplies a constant current is applied to the capacitor being tested (the 'capacitor under test' or C.u.T.). The value of the ESR can be determined by measuring the AC voltage across the capacitor. If the capacitance is sufficiently high relative to the frequency, the voltage drop due to the reactive impedance is negligible, so the voltage across the capacitor is entirely caused by the ESR. This voltage is rectified and fed to the voltmeter.

The operating principle is illustrated in **Figure 3**. Here it is assumed that the C.u.T. is rated at 100 µF and has an ESR of 10 Ω. The reactive impedance (X_C) is equal to $0.5\pi fC$ or approximately 0.0159 Ω, which is negligible relative to the ESR value of 10 Ω. The voltage measured across the C.u.T. is thus the voltage across the ESR. As the two electronic switches are actuated synchronously at the same frequency, a constant differential voltage is present at the input to the opamp. The opamp passes the differential voltage (in this case 11 mV) to its output, so the voltage at the output of the opamp is proportional to the ESR value.

Figure 4 shows a different example, with a test capacitor rated at 0.1 µF and having an ESR of zero ohms. As already noted, a fairly high frequency is used to keep the effect of the reactive impedance as small as possible so that even small electrolytic capacitors with values as low as around 0.1 µF can be measured. That makes it necessary to further reduce the effect of the initial

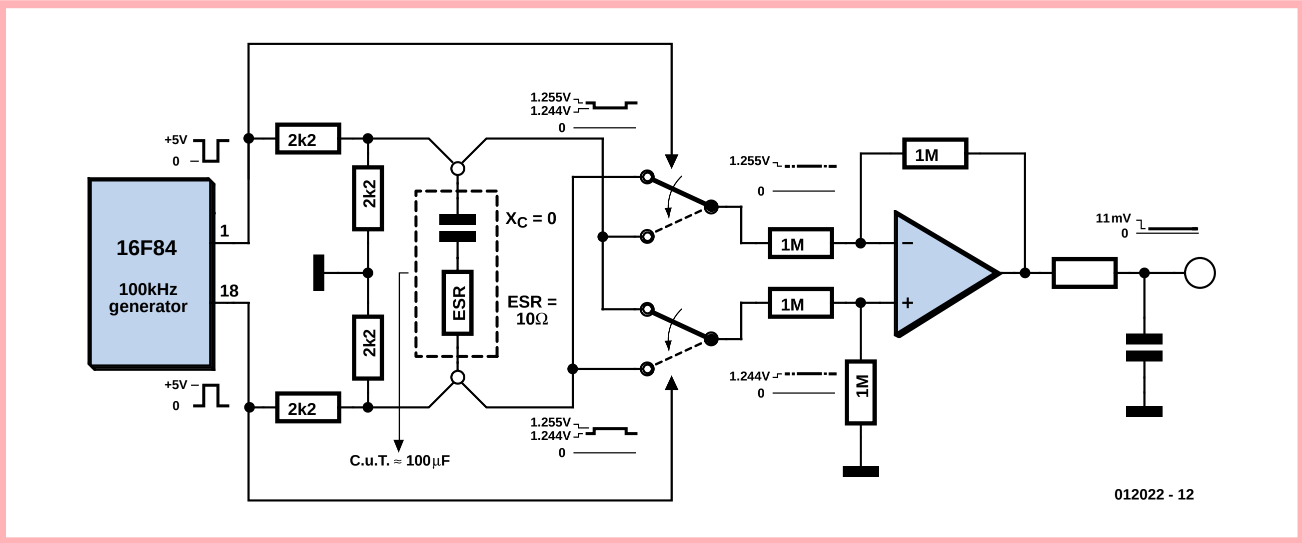


Figure 3. With a capacitor rated at 100 µF and having an ESR of 10 Ω, the reactive impedance is negligible and the ESR (which is purely resistive) determines the output voltage of the opamp.

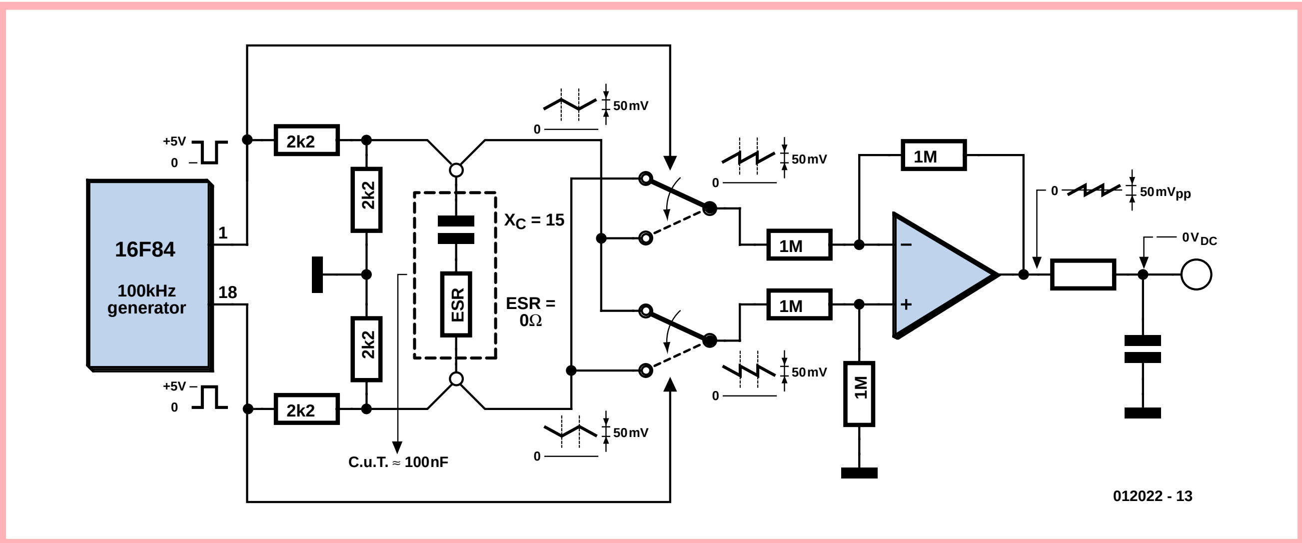


Figure 4. The situation with a capacitor rated at 0.1 µF and having an ESR of 0 Ω. Here the average output voltage of the opamp is 0 V.

integration of the voltage waveform. Here the ESR is zero and the reactive impedance is $0.5\pi fC$, or approximately 16 Ω. As can be seen, the differential configuration of the opamp causes the sawtooth integration waveform on the inputs to be summed to yield a sawtooth voltage on the output with an average value of 0 V. The resulting voltage after integration by the subsequent *RC* network is 0 V, and this value is applied to the input of the voltmeter. If the capacitor had an ESR of 10 Ω, the sawtooth voltage on the output would still have the same form, but it would be superimposed on a DC component due to the ESR. After the sawtooth was filtered out by integration, the remaining voltage would correspond to the actual ESR value of 10 ø, while the effect of the reactive impedance of 16 ø would have been eliminated.

Multiple PICs

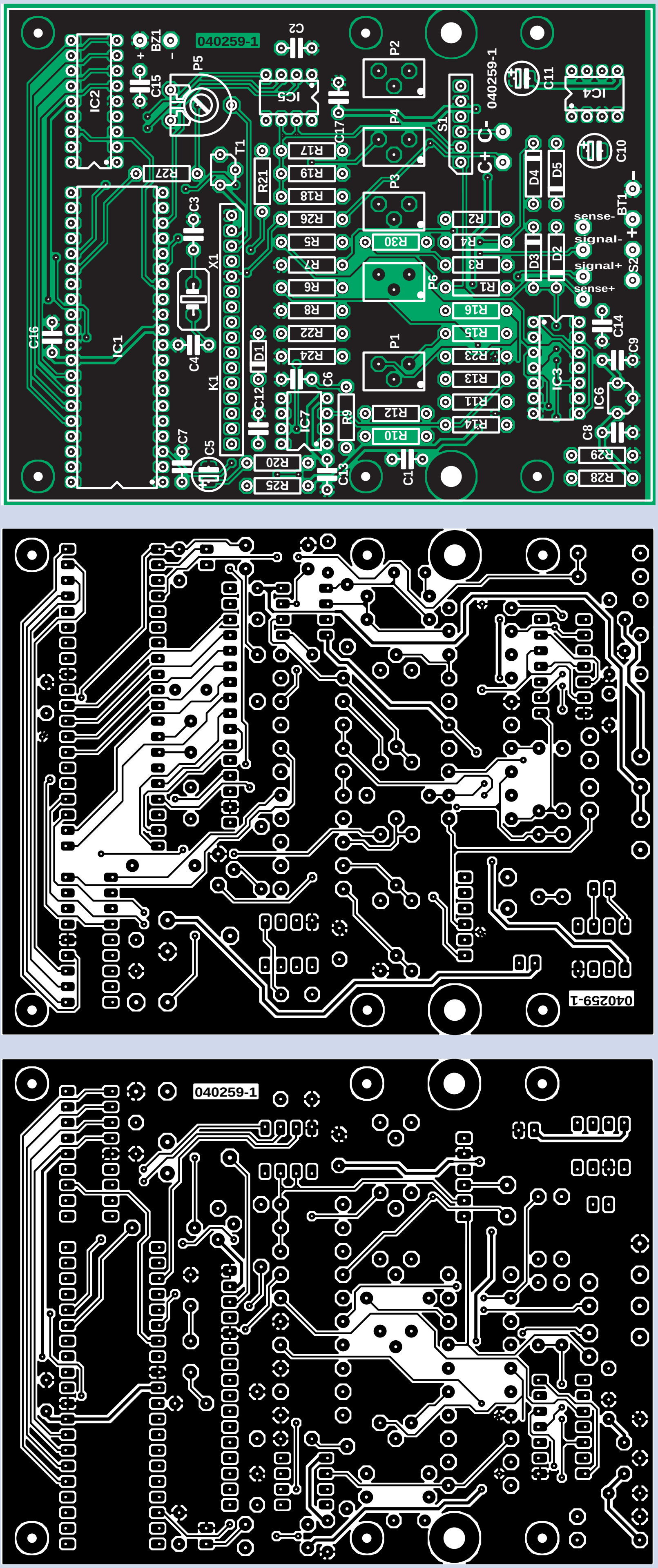
The frequency generator in the circuit of the original design has been replaced by a PIC (type 16F84). The 16F877 cannot be used for this purpose because the signal cannot be interrupted unless a DC tests is being made. The 16F84 uses the same clock oscillator as the 16F877. The advantage of using a second PIC is that it makes it unnecessary to align the 100-kHz generator frequency. It also allows the generator to be easily switched between AC and DC measurements. These modes are controlled by the 16F877, which uses interrupt routines to determine what the 16F84 has to do.

Component selection

As this circuit works with high frequencies and signal levels in the millivolt range, a differential amplifier with a low offset and large bandwidth must be used. The LF412 meets these requirements and is also not all that expensive.

The HC version of the well-known 4066 quad electronic switch IC provides fast switching times, which reduces the effect of the undesirable reactance by a factor of 2.

The best results will be obtained if the



COMPONENTS LIST

Resistors:
R1-R4 = 56Ω
R5-R8,R24 = 2kΩ2
R9,R10,R15,R16,R25,R26,R28,R29 = 10kΩ
R11-R14 = 1MΩ 1%
R17 = 8MΩ2
R18 = 7kΩ85
R19 = 120Ω
R20,R21 = 1kΩ
R22 = 82kΩ
R23 = 47Ω
R27 = 220Ω
R30 = 180Ω
P1 = 100kΩ 10-turn preset
P2 = 1MΩ 10-turn preset
P3 = 1kΩ 10-turn preset
P4 = 200Ω 10-turn preset
P5 = 25kΩ preset
P6 = 100kΩ 10-turn preset

Capacitors:
C1 = 1nF
C2 = 47nF
C3 = 22pF
C4 = 27pF
C5 = 10µF 16V radial
C6 = 220nF
C7,C8,C9,C12-C17 = 100nF, lead pitch 5mm
C10,C11 = 10µF 16V radial

Semiconductors:
D1 = zener diode 5V6 500mW
D2-D5 = 1N4007
IC1 = PIC16F877-20/P, programmed, Publishers order code **040259-41***
IC2 = PIC16F84A-20/P, programmed, Publishers order code **040259-42***
IC3 = 74HC4066
IC4 = ICL7660
IC5 = TLC555
IC6 = 78L05
IC7 = LF412CP
T1 = BC557

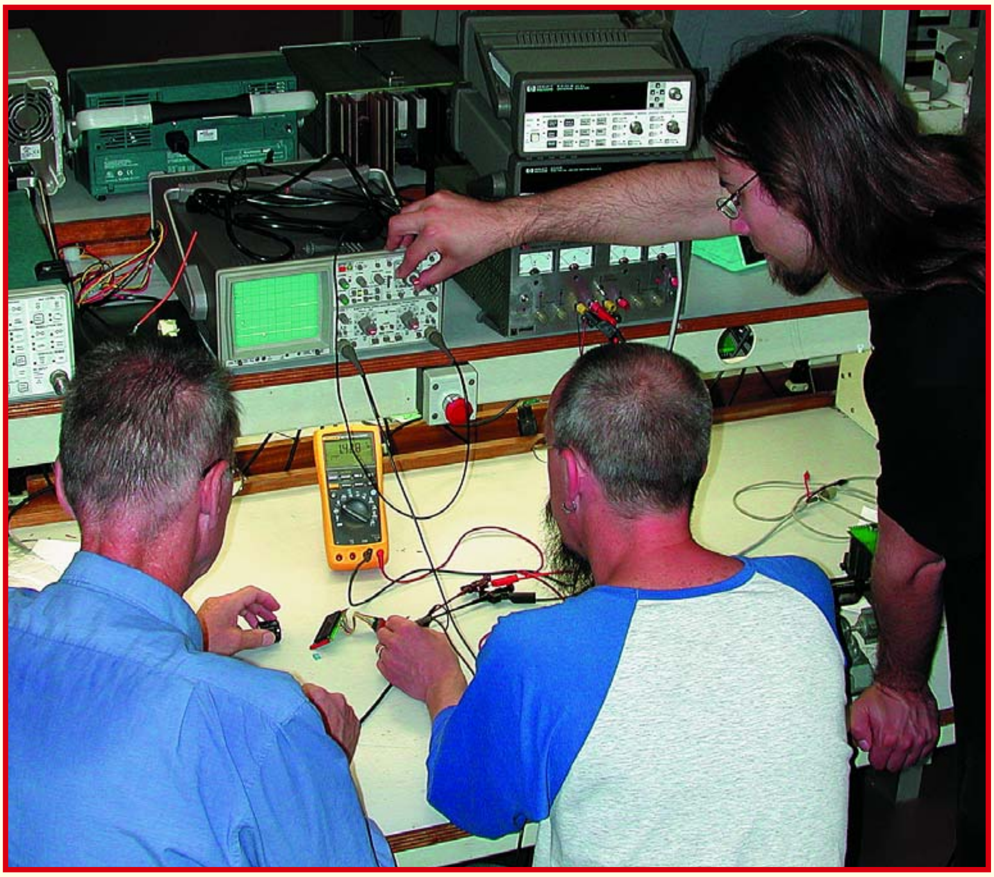
Miscellaneous:
Bz1 = AC (passive) piezo buzzer
S1 = switch, 2 changeover contacts
S2 = switch, 1 make contact
K1 = LCD module, 2x16 characters (e.g., Digikey # 153-1078-ND)
X1 = 20MHz quartz crystal
2 wander sockets for banana plug
Measurement cable
Enclosure, e.g., SERPAC H75 (Digikey # SRH75-9VB-BD)
PCB, Publishers order code **040259-1***
Disk, source- and hex-code files, Publishers order code **040259-11*** or **Free Download**

* see Elektor SHOP page or www.elektor-electronics.co.uk

Figure 5. Double-sided circuit board layout and component layout for the ESR/capacitance meter.

Keep smiling

Even if we run into major problems in our lab we always try to see the positive side of things — if only to convince ourselves that a troublefree life would be boring. Engineering Flemming Jensen's ESR/C Meter from blueprint right up to publication in print was a far from smooth process and with hindsight we have to admit having made an error or two when assembling the prototype. Nothing too serious of course, but still...



Karel Walraven

The first life signs of the circuit were hopeful. The display produced legible texts, so at least the microprocessor is running its program. Then came the problems. Measuring capacitors was troublesome if not impossible — usually, the display remained stuck at one firm '0' and that's no incentive to build an ESR/C Meter. So we ran the usual checks on the board. Always start by measuring the supply voltage directly on the IC pins — both the +5 V and ground rails should be inspected. Next up is the microprocessor clock and *bingo* there we got 6.66 MHz instead of the desired 20 MHz – the quartz crystal was cheerfully resonating at its fundamental frequency instead of the third overtone. Sometimes this is a false reading however, the 50-pF scope probe capacitance wreaking havoc at the oscillator input. However, a rock solid 6.66 MHz was measured at the oscillator *output* and we were using a 1:10 probe so extra capacitive loading would be small. This leaves several other fault factors to be considered: the PIC may have been programmed for 'standard crystal' instead of 'high speed crystal', or the two xtal loading capacitors may be too large. Also, the crystal itself may be at fault, some will simply refuse to switch to overtone resonance. In our case, it turned out that the PIC was incorrectly programmed and the problem was solved quickly. Alas... the display now greeted us with total gobbledygook. Strange, but still reassuring to know at this point that there were no display wiring errors — after all, the display had worked just fine we corrected the clock frequency. A timing error? LC displays may not be driven too fast. For example, the datasheet tells us to observe a minimum length of 450 ns for the enable pulse. Internally, a PIC operates at the xtal frequency divided by four, so in theory, at 20 MHz, it is able to supply new data on its I/O pins every 200 ns. That looked like a plausible explanation of the phenomenon we were faced with. This kind of error easily creeps into a design. The test circuit runs fine at a lower clock speed, *hooray*, the design is 'quickly optimised' while drawing the schematic and then... a final check of the pulse timing is forgotten. However, it could also be an undiscovered error — some LCDs have no problems with 200-ns pulses, while others from a different series or manufacturer will hang.

We cast a critical eye on the LCD driver routine, created a longer enable pulse and reprogrammed the PIC. The LCD then worked as desired. By itself, that is, because after all this hard work, the readout was still meaningless. We quickly found out that the measured values were invariably negative instead of positive, and the microprocessor programs was known to turn any negative value into a solid zero. In theory, this can happen if the phase of the synchronous detector has been swapped over. After a lot of searching and debating, we agreed that that was not the case. Wild theories were heard then in the lab, until it transpired that the switch selecting between capacitance and ESR measurement was incorrectly wired, causing a mighty offset in the detector. Nobody had thought of such a simple exchange of two wires!

The moral of the story: always check obvious matters first. Do not fear the worst and certainly do not dig deeper than necessary!

recommended components are used. However, the performance is still acceptable with a normal 4066.

Compact construction

Thanks to the use of two microcontrollers, the size of the overall circuit remains relatively small, so the printed circuit board designed for the circuit (**Figure 5**) has quite modest dimensions.

There are only a few components that have to be connected to the circuit board via short leads. The LCD module is connected to K1. Switch S1, which is used to select either capacitance or ESR measuring mode, is wired to connector S1 on the circuit board using six short leads. Points C+ and C– are connected to two measurement terminals or sockets located on the front side of the enclosure. The pins marked Signal+, Signal–, Sense+ and Sense– are for connecting the additional ESR test leads with their separate sense lines in order to measure capacitors while they are still connected in a circuit (see **Figure 6**).

The battery and power switch S2 (BT1 and S2, respectively) must also be connected to the circuit board, as well as the beeper (BZ1).

Test probes

Four-wire measurement is used here to compensate for the voltage drop in the test leads. Each of the test leads has two screened conductors, consisting of a signal lead and a sense lead (see **Figure 6**). This prevents the measurement from being corrupted by hum, noise or ESD interference and allows a stable zero calibration to be implemented.

Calibrating the ESR meter

The offset is set to 40 mV instead of 0 V because the ADC cannot handle negative voltages. Short the test probes together and connect a voltmeter to pin 7 of the LF412 (IC7). Then adjust P1 for an offset voltage of 40 mV. The resulting offset can then be compensated by the software. However, that requires shorting the probes together when the meter is switched on in the ESR mode. The offset voltage is converted by the ADC. The resulting value is stored in an EEPROM and subtracted from the measured ESR value when a measurement is made.

Switch the meter to the ESR mode and switch on the power. You can use P5 to adjust the contrast of the LCD module. Short the probes together when you are requested to do so. Now connect the probes to a 10-Ω resistor and adjust P6 until the display shows a value of 10 Ω. Connect the meter to several working capacitors in turn, without and without a 10-Ω resistor in series, to verify that the meter is working properly.

Calibrating the capacitance meter

You need a pair of precision capacitors to calibrate the capacitance meter. A value of 470 pF / 1% is suitable for the picofarad range, and a value of 220 nF / 1% can be used for the nanofarad range. Both values can be obtained at a reasonable price from various vendors, such as Farnell. Do not use values of 1000 pF or 1000 nF, since that can cause the display to flicker between 999 pF and 1.00 nF or 999 nF and 1.00 µF, respectively. The easiest way to adjust the range above 10 µF is to use a commercial capacitance meter. An alternative method is to use the formula $t = RC$ and a simple stopwatch.

Keep the meter away from transformers and strong 50- (60-) Hz fields. Switch on the meter, connect it to the 470-pF capacitor, and use P2 to adjust the value on the display to match the value of the capacitor. Next, connect the meter to the 220-nF capacitor and use P3 to adjust it to the right value. Finally, you can use P4 to set the right value for your reference electrolytic capacitor.

After that the meter is ready for use. From now own, no capacitor new, old or NOS (new old stock) will hold any secrets for you.

(040259-1)

Things to pay attention to

- Always discharge the capacitor before connecting the meter to it.
- Switch on the meter before connecting it to the capacitor to be measured.
- Four measurements are made on capacitors with values greater than 10 mF. After that, the meter displays 'Ready', and it must be switched off and back on to make a new measurement.
- Be patient when measuring capacitors with very large values. It takes approximately 10 minutes to measure a 370-mF capacitor.

Warning

Although the inputs of the meter are protected by diodes, it is good idea to discharge large capacitors before measuring them. The risk of burning out the protection diodes is particularly high with filter/buffer capacitors used in power supply circuits.

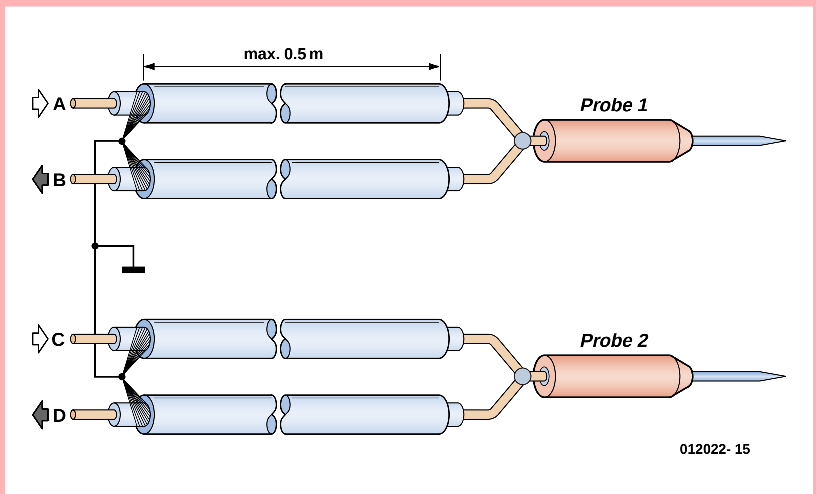


Figure 6. How to build the two dual shielded measurement leads that connect the probes to the actual instrument.