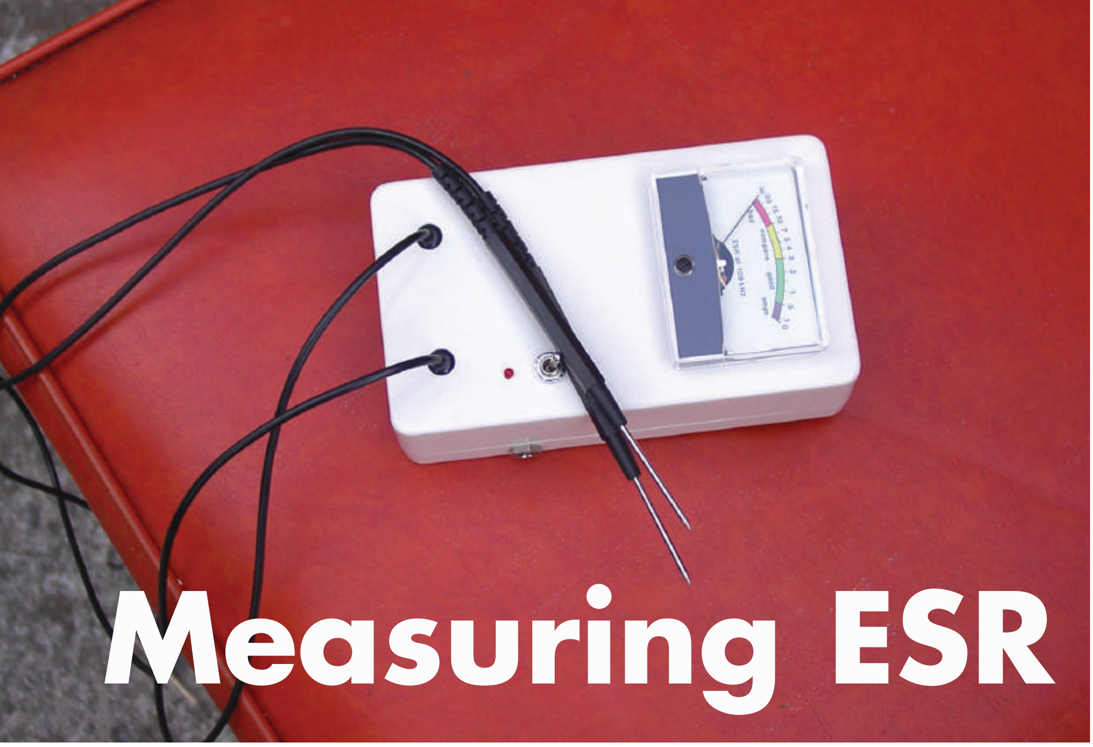


Measuring ESR

The equivalent series resistance (ESR) of an electrolytic capacitor is a reliable indication of its condition. Alan Willcox's first ESR meter design, published in these pages some five years ago, was very popular. This Mark 2 version incorporates several improvements, in particular a simpler oscillator design and single-battery operation

A simplified equivalent circuit of an electrolytic capacitor, see Fig. 1, is usually shown when providing a brief explanation of what ESR is all about. In addition to the ideal capacitor Xc, a second component is present. It has a significant effect on the capacitor's performance, and is referred to as the equivalent series resistance (ESR). Electrolytic capacitors are used mainly for decoupling and, to a lesser extent, for signal coupling. This being so it's important that, for optimum performance, the impedance (AC resistance) of the capacitor is as low as possible.

An electrolytic capacitor's ESR is mainly determined by the condition of the electrolyte (paste) that separates its foils. The electrolyte increases the component's capacitance but, when it deteriorates, it increases the impedance present. The lower the ESR, the better the capacitor!

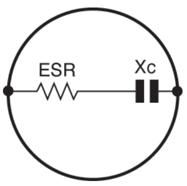


Fig. 1: Simplified equivalent circuit of an electrolytic capacitor. Xc represents an ideal capacitor. Its reactance moves towards zero ohms as the frequency increases. $Xc = 1/(2\pi fc)$. The value of the equivalent series resistance ESR is determined mainly by the condition of the electrolyte.

Electrolytic capacitors used in switch-mode (chopper) power supplies and those mounted close to heatsinks tend to run hot. Heat is inclined to dry out the electrolyte and, in time, a capacitor may develop a high ESR. This will itself introduce a power loss – and more heat! The effect of failure of this type in a power supply can be catastrophic. For example, if the capacitor is in the HT monitoring section of a TV set's power supply the HT voltage might rise, damaging the line output transistor and maybe the field output IC.

This type of problem is more significant when a set is started up from cold, as the condition of a faulty electrolytic capacitor is worse when cold. Thus cold checks are by far the best approach to testing! Problems with electrolytic capacitors, particularly those used in switch-mode power supplies, are caused not so much by a change of capacitance value as by an increase in the component's ESR. Thus removal of a suspect capacitor to check it with a conventional capacitance meter is largely a waste of time. Furthermore a faulty capacitor may be overlooked because its capacitance value has hardly changed. An ESR meter gets around this problem by using a test frequency (or pulse rate) that's high enough for the capacitive reactance to be almost zero ohms, leaving just the ESR as the measurement.

Measuring ESR

ESR obviously cannot be measured directly, using a conventional ohmmeter, so a means has to be found to 'get to' the ESR that's hidden inside the capacitor. A number of ready-made meter designs and kits are now available for measuring the ESR of an electrolytic capacitor in-circuit, using cold checks. They achieve success and simplicity in varying degrees. Use of a suitable meter enables cold checks to be made without the risk of any further damage occurring. Strictly speaking it is the impedance that's being measured but, over a particular range of test parameters, it can be shown that this presents more or less the same value.

It is all too easy to over-complicate things when it comes to ESR. There are those who argue that ESR meters don't measure the ESR precisely. But, in the real world, how precise does the reading need to be? It really doesn't matter. The service engineer just needs to know, as quickly as possible, which capacitor is causing the trouble. An ESR meter does just that! Once technicians have become accustomed to using an ESR meter, they wonder how they ever managed without one. Although the ESR varies somewhat with frequency, we can in practice regard it as being a constant in-phase component, and calibrate our meter using fixed resistors. This is useful, as the meter will also serve well as a low-ohm meter.

So, if an ESR meter doesn't measure capacitance, what readings can we expect from good and bad capacitors using such a meter? How do you know whether a capacitor is OK or not? The curve shown in Fig. 2 gives a practical idea of the sort of ESR readings that should be obtained with good capacitors of different values. There is no hard-and-fast rule however – it's not an exact science. All it needs is a bit of getting used to. This doesn't take long: just measure the ESR of a few new capacitors. Try 1, 10, 47, 100, 470 and 1,000μF. You will find that values of 47μF and above measure quite low, 0·5Ω or less, with the buzzer coming on (the buzzer turn-on point can be varied, see later). The important point is just how low capacitors with values of 47μF and above measure. At 470μF and over, the reading is close to zero ohms. If, in practice, a 1,000μF capacitor produces a reading as high as 0·5Ω, it's no good!

Analogue or digital display?

Digital methods of measurement and display are generally regarded as providing more accurate results. For many applications this is true, but it's not necessarily so with ESR measurement. There are two ways of interfacing the capacitor being tested and the meter. The capacitor can be connected in parallel with the test signal source, as shown in Fig. 3(a), or in series, see Fig. 3(b).

If a digital ESR readout is used, the capacitor must shunt the test signal. With an ideal capacitor, the result will be zero ohms and zero display: with a bad capacitor there will be a high reading, with little shunting away of the test-signal. We are interested in ESR values of 3Ω or less, but a digital meter gives readings far higher than this. It's not a major problem, but can give rise to superfluous information as far as ESR measurements are concerned. A more important factor is that the parallel method results in a significant increase in the readings obtained because of excessive sensitivity to the inductance of the test leads. This can be overcome by fitting two leads to each probe. It provides cancellation to a large extent, but this solution is a bit clumsy in use and to construct. The series method of interfacing does not suffer from this drawback, so the use of conventional test leads becomes acceptable. I don't know why this effect occurs – I just found out the hard way.

Although we have become used to digital readouts nowadays, for ESR measurement there is little doubt that a moving-coil meter is the best type of display. It gives a rapid, easy-to-interpret indication of the condition of the capacitor. After some experience of using it, one gets to know where the pointer should approximately be with good capacitors of different values. Indeed a meter scale becomes almost unnecessary. I know of people who have used this type of meter quite satisfactorily without ever having taken the trouble to fit a scale dedicated to ESR measurement.

To repeat: it's not an exact science but, with some experience,

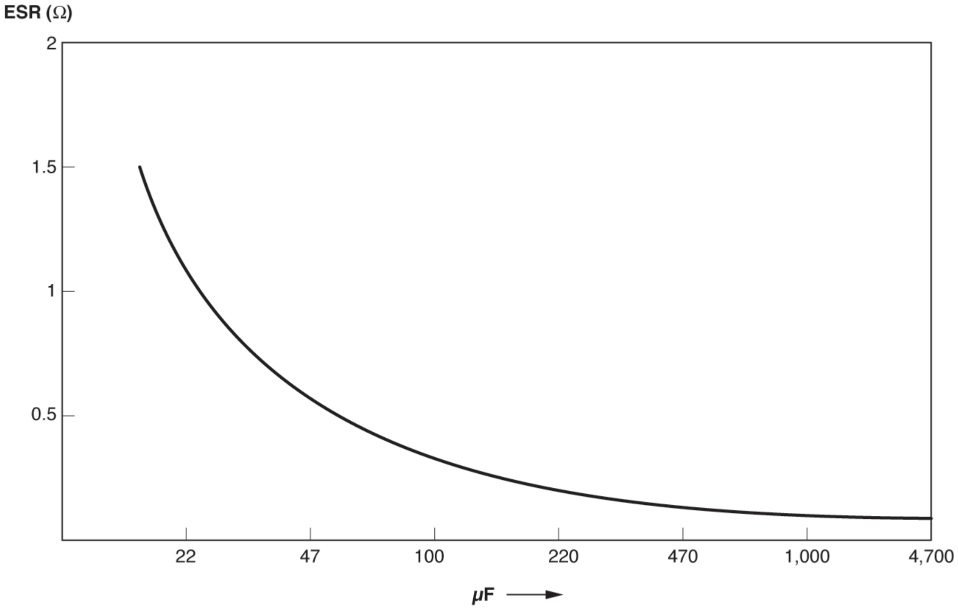


Fig. 2: Plot of ESR vs. capacitance. The curve is typical of 63V working capacitors. With higher voltage ratings the ESR is somewhat higher.

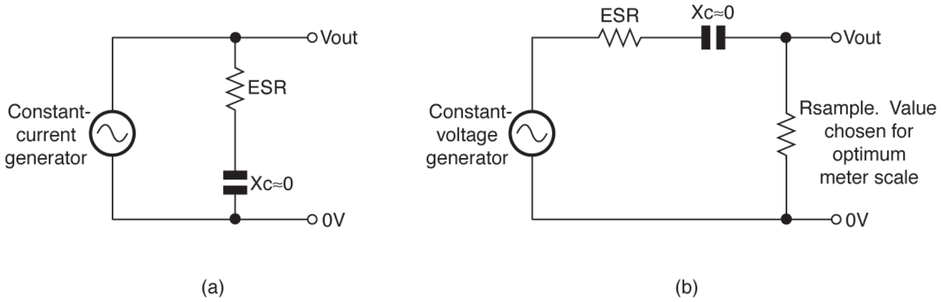
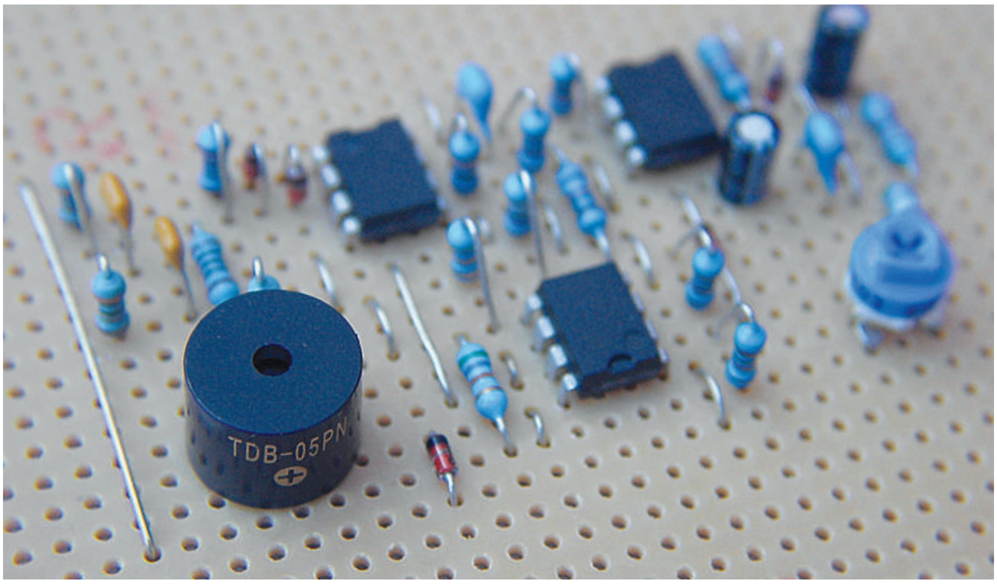


Fig. 3: The shunt type of interface used with a digital display is shown at (a). Zero ESR = zero display. The output is directly proportional to the ESR. This method is sensitive to lead inductance.

The series type of interface used with an analogue display is shown at (b). Vout is non-linear, which is exactly what we require to avoid range-switching. The scale is expanded in the low-ohms region. Vout is proportional to Rsample/(Rsample + ESR). So, if the value of Rsample is 3Ω, this would be the mid-scale reading. Just about ideal!



Layout of Alan Willcox's Mark 2 ESR meter on stripboard. The Mark 2 incorporates several improvements, including a simpler oscillator design and single-battery operation.

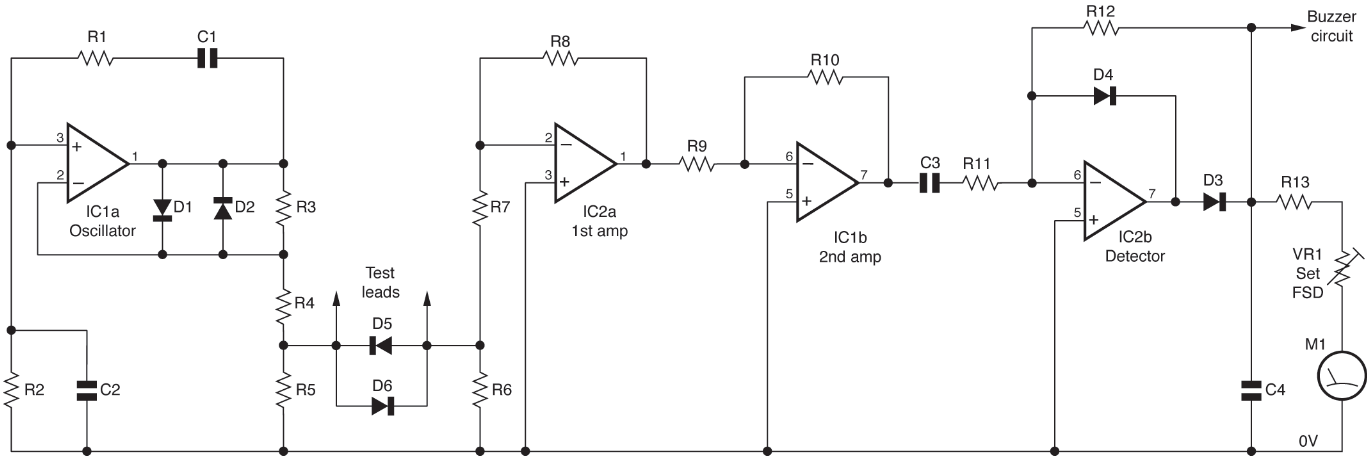


Fig. 4: The basic ESR meter circuit, new version. IC1 and IC2 require positive and negative supplies at pins 8 and 4 respectively. Further circuitry is required, see next month, to generate the split-rail supply and provide a buzzer comparator.

one soon gets to know which capacitor is causing the trouble by knowing roughly where the ESR meter's pointer should be with a good one. One argument that's sometimes put forward against the use of a moving-coil movement is that the movement will be damaged should the meter fall off the bench. I have a solution to this problem. If you are inclined to be clumsy, attach a piece of string between the meter and the bench, long enough so that the meter comes to a halt just before it hits the deck but not so short that you don't get a bit of a jolt to serve as a reminder.

Test-signal parameters

Amplitude: To test for ESR or for actual capacitance there are no constraints on how low the test signal can be as far as the capacitor is concerned. Taking into account power consumption, and the problems associated with low-level signals of the order of microvolts, noise considerations etc., a level of about 5mV peak-to-peak seems to be a good compromise.

Frequency: The time period should be short enough to zero out the capacitive reactance. 100kHz is a popular choice. At about this frequency the ESR and impedance converge with the type of capacitors in which we are interested. Apart from that consideration, 100kHz is about the top frequency at which a predictable gain of up to ten times can be obtained with readily-available, low-cost operational-amplifier ICs.

Remember that if the rate-of-change of the voltage is fast enough, any capacitance will provide negligible opposition (Xc) to it.

Waveform: Analysis of a squarewave has been used, and I've tried this myself. The results are a bit unpredictable however. I had a lot of trouble trying to preserve the waveform intact at the mV level to give a useful, predictable indication. It's not worth the effort. A sinewave is so easy to generate and amplify that I cannot see any justification for incorporating squarewave analysis into the design of an ESR meter.

An improved ESR meter

The meter presented here is similar to the one described in the March/April 1999 issues of *Television*. Since then the use of an ESR meter to check quickly for faulty capacitors has become well established. The original circuit works well and has stood the test of time, but feedback from the trade has prompted me to make some improvements. These include single-battery operation and improved temperature stability. The new circuit remains stable down to 6·2V, and consumes about 13mA. Because of the improved temperature stability of the new oscillator circuit, there is no need for an externally-available set-zero control.

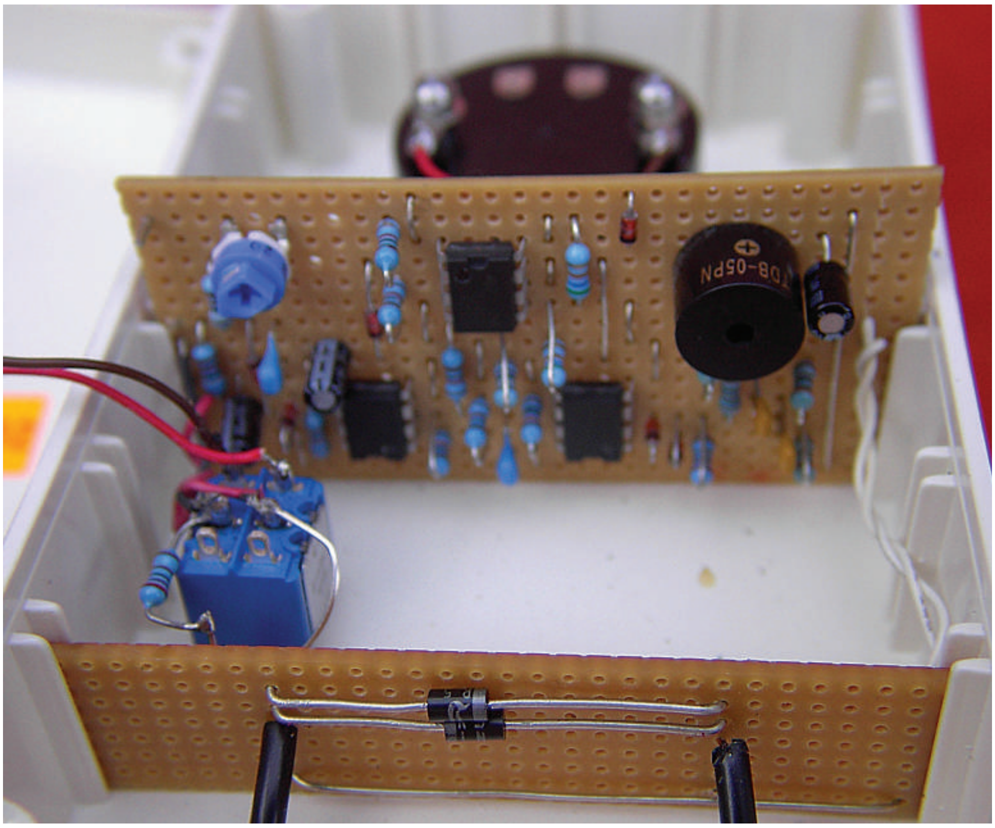
The oscillator circuit

An HF oscillator or pulse generator with a stable output over a reasonable supply voltage range is the heart of every ESR meter. IC1a in the new circuit, see Fig. 4, is the sinewave oscillator in this design. The simplest way of generating a sinewave is to incorporate in the the oscillator's positive-feedback path a network originated by Max Wien in 1891. It ensures that the feedback is an in-phase component at only one frequency, which is fixed by the *RC* values used. At very high frequencies C2 presents a low-impedance path, while at lower frequencies C1 becomes an effective open-circuit. At some point in between there will be maximum output from the network C1, R1, C2, R2, which is referred to as a Wien bridge. The *RC* values used here result in oscillation at about 100kHz.

There are two simple methods of stabilising the output level with an op-amp Wien-bridge oscillator. The method traditionally used is to include a bulb in the negative-feedback path (between pins 1 and 2 here). This was the approach used in my 1999 design. There has been some misunderstanding about the bulb, because of the different specifications used in US literature. I went into the matter in some detail in the 1999 articles. The correct specification is 28V, 24mA.

The principle behind the use of a tungsten bulb is that its resistance increases with the current that flows through it. If a bulb's resistance is measured, the small current from the ohmmeter will increase its resistance. When employed correctly in this application the bulb does not come anywhere near incandescence. I decided to use the lamp then because of its elegant simplicity and extremely low distortion figure (0·0025%). With the new design I wanted to reduce the operating voltage of the whole meter so that a single PP3 battery could be used as the power source while still achieving very low power consumption. The problem with the use of a bulb is that in these conditions the bulb's temperature is not sufficiently far away from the ambient temperature to ensure good stability. So this time I decided to use the brute-force method of diode stabilisation (D1, D2).

The idea here is that when the output from the oscillator rises above the conduction point of the diodes the negative feedback increases, the output settling at an amplitude which depends on the characteristics of the diodes. In this case the net result is a sinewave source signal across R5 with an amplitude of about 6mV peak-to-peak. Diode stabilisation introduces greater distortion, but this is not important here. To maintain oscillation, the value of R3 must be over twice that of R4. A preset resistor, adjusted to just sustain oscillation (lowest distortion), is usually used in the R3 position. I decided to use a fixed value that's a few ohms on the high side, to ensure reliable oscillation regardless of distortion.



Internal view of the new ESR meter. The test lead connections are at the bottom, with protection diodes between them.

Interface with the capacitor being tested

The interface with the capacitor being tested is the crucial part of the meter. It took me a long time to get this right. See Fig. 5. The waveform across R5 (the source resistor) is not an ideal, constant-voltage source, because of the need to include the sample resistor (R6), whose value must be comparable to the ESR values in which we are interested. The ESR of the capacitor being tested forms part of a potential divider with R6. Thus if, for example, a good 1,000μF capacitor with an ESR of about 0·1Ω is connected for test, R6 is effectively in parallel with R5. This means that the supply-signal source is less because, when a capacitor is being tested, the constant-current source to R5 is shared with the ESR and R6 in parallel.

The voltage waveform developed across R6 as a result of the current through the capacitor being tested is amplified and then detected by the rest of the circuit. If the ESR of the capacitor being tested is equal to the value of R6, half of the supply waveform will be passed on. The supply waveform is not independent of the load however. If the ESR is less than the value of R6, as in most cases it is, the waveform voltage across R6 increases.

As the ESR rises above the value of R6, the latter becomes less effective. The result of all this is a non-linear scale, expanded at the lower range and somewhat logged out. This is ideal for the present application, because in some cases it is important to be able to distinguish between a very low value, close to zero, and one of about 0·5Ω.

I have achieved low current consumption and circuit simplicity by using the feedback current and compromising somewhat on the ideal, constant-voltage source.

Next month

In the concluding instalment next month I'll complete the circuit description, deal with some practical points and protection methods, provide a detailed components list and a stripboard layout. ■

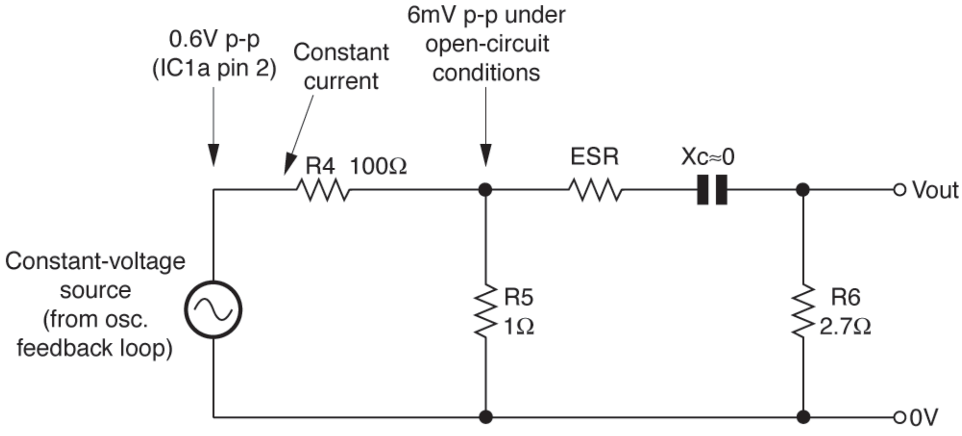


Fig. 5: The method of test capacitor interface used in this meter. The source voltage is not a true constant voltage because of the need for R6, whose value must be comparable to the ESR of the capacitors in which we are interested.

Current economy and circuit simplicity are achieved by using feedback current from the oscillator circuit as the source fed to the capacitor under test. The output is inversely 'logged' out in relation to ESR.

Measuring ESR

This second, concluding instalment completes the description of Alan Willcox's latest ESR meter, with a suggested stripboard layout and component specifications

In Part 1 last month I dealt with ESR and its measurement, and described the significant features of my latest ESR meter design. I'll start this month with a description of the basic circuitry used.

Circuit description

Fig. 4 (see page 78 last month) shows the basic ESR meter circuit. The important features of the oscillator and test interface sections were covered last month. There is no need for a regulated power supply. Just to remind you, the amplitude of the HF output waveform obtained from the oscillator (IC1a) is set by the characteristics, which are virtually temperature-stable, of the two diodes D1 and D2 in the negative-feedback path between pins 1 and 2. The amplification and detection levels provided by the other stages are set by the ratio of the source and feedback resistor values used. This is standard operational-amplifier practice. The way in which operational amplifiers work was covered in some detail in my articles in the March/April 1999 issues, so only a brief description is given here.

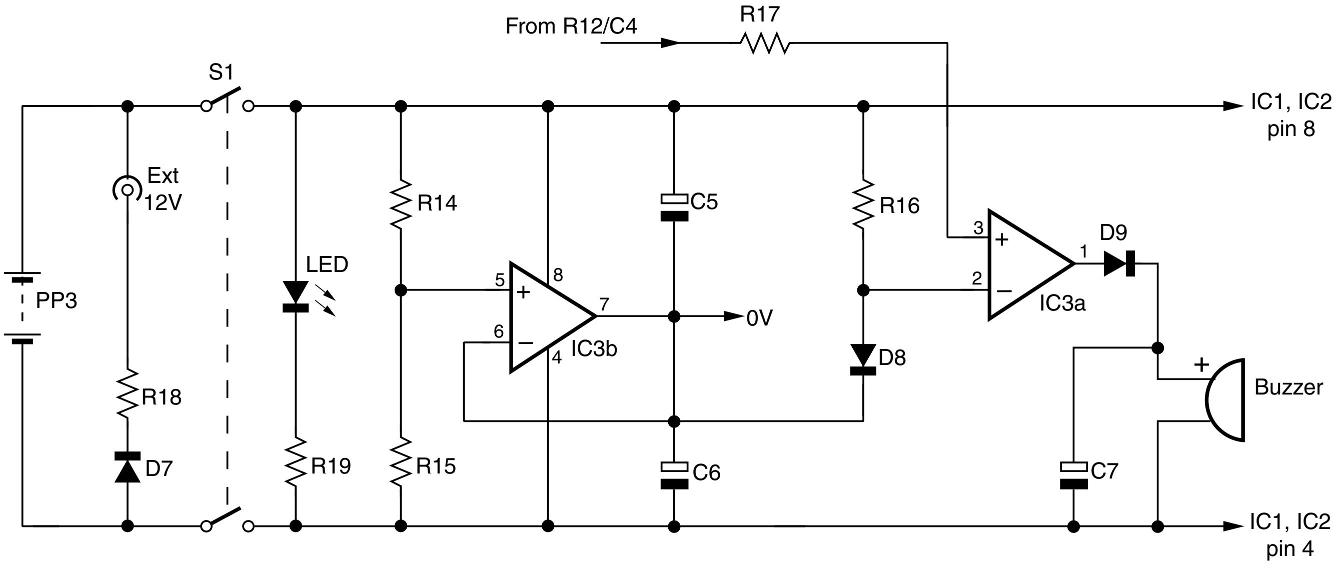
The frequency of the Wien-bridge oscillator is approximately equal to $1/(2\pi RC)$ when resistors R1 and R2 and capacitors C1 and C2 have equal values. At this frequency there is no phase shift across the bridge and thus maximum positive feedback. At resonance, the upper section of the network (R1, C1) has twice the impedance of the lower section (R2, C2), so there's a transmission loss of 1/3. To sustain oscillation, the overall gain (ALC) must be greater than unity. The transmission loss through the network is offset by the gain determined by the ratio 1 + (R3/R4). In this circuit the ALC would be more than the three times required were it not for diodes D1 and D2, which override the effect of R3 as mentioned above.

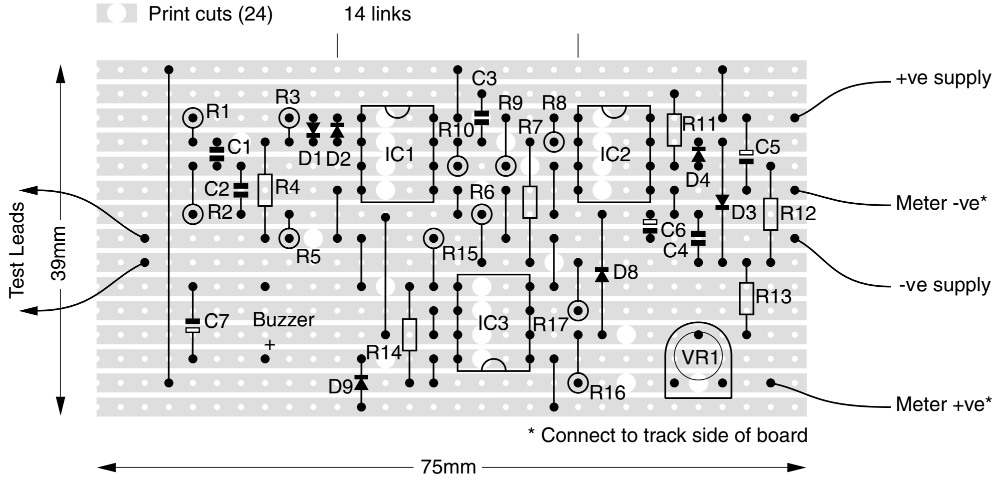
The following two stages of amplification (IC2a and IC1b) are straightforward, with no need for correction circuitry. Capacitor C3 in the feed to the detector stage (IC2b) is included to remove any DC component and also to reduce sensitivity to low frequencies (mains hum or whatever). R12 sets the gain in the detector stage. Because of the high intrinsic gain of an operational amplifier, the forward voltage drop across detector diodes D3 and D4 is overcome and detection at even mV level is not a problem.

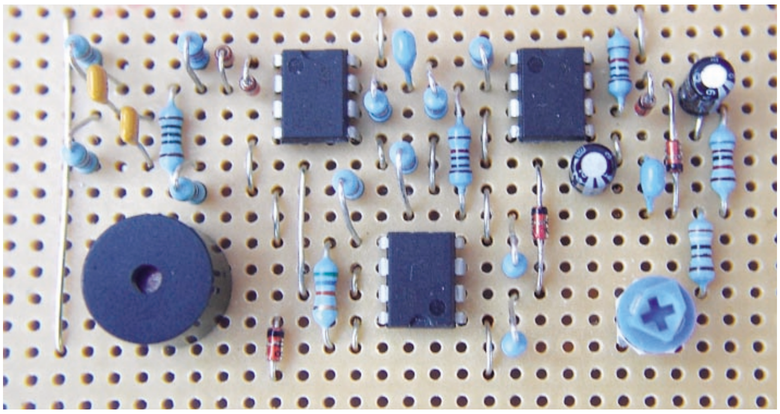
Split-rail generator and buzzer

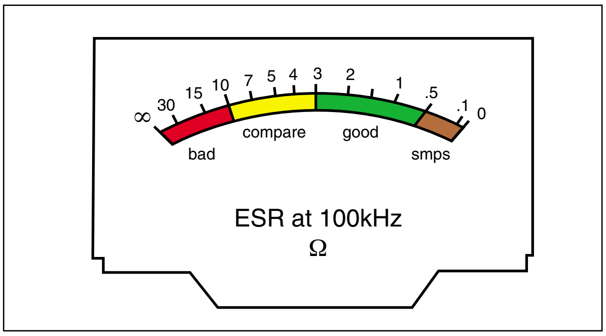
That is all there is to the basic circuit. But the operational amplifiers require positive and negative supplies. This requirement is provided by IC3b, see Fig. 6, which is configured as a voltage-follower. There is 100 per cent negative feedback (pins 7-6), so the output voltage must settle at half the supply voltage, set by the equal ratio of R14 and R15. I was pleased to find that the circuit remains stable with outputs as low as ±3·1V. This lower supply voltage range is quite consistent.

IC3a is configured as a voltage comparator. When the ESR reading is less than 0·5Ω, the output from the detector goes higher than the forward voltage drop across D8. The output at pin 1 of IC3 therefore









Top – Fig. 6: The split-rail generator and buzzer comparator circuits.

Centre – Fig. 7: Suggested layout on stripboard.

Left – Layout of the prototype meter on stripboard

Bottom – Fig. 8: The ESR meter scale, shown full size. (58mm)

goes high, activating the buzzer. The ESR level at which the buzzer operates is set by the overall gain. This point can easily be changed by altering the value of R12. If its value is increased, the overall gain rises and the buzzer will operate at a higher ESR level.

The value of 100Ω for R18 is chosen to limit the current from an external 12V source to a rechargeable battery to the trickle level. The overall consumption is so low that, if you are one of those who remember to switch off battery-powered equipment when it's not in use, an ordinary battery is OK and will last for quite a long time.

Although the basic meter circuit is happy with a supply between 6-30V, the buzzer and LED won't be. The value of 2·7kΩ for R19, which is in series with the power-on indicator LED, gives good brightness over a supply range of 6-9V, with only a few mA drawn.

Practical points

As the meter operates at 100kHz, any inductance in a circuit being checked will produce a high-impedance reading. If an EW coil produces a reading, it has shorted turns. Another use of the meter is where the line output transistor appears to be short-circuit. A quick check with the meter will isolate it – if the short is elsewhere, in most cases the impedance of the line output transformer will be in the way and will result in a high reading. If there's a low reading, the transistor is most often the culprit.

ESR meter users have come up with new applications. The non-polarised, high-voltage capacitors used in the line output stage (tuning etc.) can be tested. I've not taken the trouble to design a new meter scale for this application, as I have no practical experience of such checks. It seems to me that if such a capacitor gives any reading at all other than short-circuit it will be OK. This type of capacitor does not change value.

I would like to think that the present article just about sums everything up with respect to the

Parts list

Item	*Value/type*	*CPC order code*	
R1, 2	3kΩ	REMFR4 followed by the value	
R3	220Ω		
R4	100Ω		
R5	1Ω		
R6	2·7Ω		
R7, 9, 11, 16, 17	10kΩ		
R8, 10	100kΩ		
R12	*68kΩ		
R13	3·9kΩ		
R14, 15	56kΩ		
R18	*100Ω		
R19	*2·7kΩ		
All 0·5W, 1% metal film			
VR1	10kΩ cermet preset	RE01881	
C1, 2	470pF low-loss high-stability**	CA02068	
C3, 4	0·1µF ceramic multilayer	CA02098	
C5, 6, 7	22µF, 16V	CA01613	
D1, 2, 3, 4, 8, 9	1N4148	SC1N4148	
D5, 6	1N4004	SC1N4004	
D7	1N4002	SC1N4002	
IC1, 2, 3	TL082CN	SCTL802	
LED	3mm Superbright	SC00023	
M1	100µA moving-coil	PM11119	
S1	Miniature toggle switch	SW-Z201/Z	
Buzzer	5V DC	LS00654	
Case	ABS box	EN55030.	See text
Test leads	2mm plug to probes	IN00772.	See text
Veroboard		PC00046	
Spot face cutter for Veroboard		PC00066	
PP3 battery clip lead		BT02187	
High-current protection choke		PW00037.	See text

*The value of R12 sets the turn-on point for the buzzer, see text. R18 sets the charge current, see text. R19 is chosen for good brightness with the LED specified.

**For correct oscillator operation C1 and C2 must be of the type specified.

quick in-circuit location of faulty electrolytic capacitors. If anyone contemplates the design of a PCB for the project, it is important that separate operational-amplifier chips are used for the oscillator and the first amplifier stage – to avoid between the oscillator and the sensitive first amplifier stage. Fig. 7 shows a stripboard layout for the meter's circuitry. Fig. 8 shows the meter scale.

Don't be tempted to use plugs and sockets for the test leads – you would in time get problems in the low-ohms range. Soldered connections should be used throughout. I use 2mm test leads with the plugs cut off. Make sure that you file the probes to give sharp points. The coating that's on them has a significant resistance.

The case specified in the parts list is a bit on the deep side. To achieve a slimmer appearance, I bought another case, type EN55029 (too slim), and combined the halves. This might sound extravagant, but you still end up with two cases and they cost only about £2.

Protection methods

In a letter in the August issue this year Jim Littler suggested wiring an inductor across the test lead terminals to protect the meter should it be connected to a charged capacitor. I can see no problem with this, and followed up with a letter in the September issue. If a value somewhat lower than the 150µH recommended there is used, producing a reading of say 30Ω, this reading will be present each time the meter is switched on and you will know that it is working correctly. It will not affect the use of the meter. We are only interested in values that are much lower.

If this method of protection is used with a digital meter, the display will settle at a fixed reading. This will show that all is well with the meter and will also eliminate superfluous readings. In the case of a moving-coil display, it will double-up as a power-on indicator.

The use of a circuit protector in series with the test leads has been suggested. The problem is that it would tend to blow too easily and require frequent replacement.

To reiterate, diode protection (D5, D6) should always be included.

Any comments about high-current choke protection, which seems to be a unique idea, and on ESR measurement in general would be welcome.

You can reach me by email at alanesr@hotmail.com

I think that covers everything. ■