Design of an ESR Meter

The subject of an electrolytic capacitor's ESR has generated a lot of interest in recent issues. Alan Willcox has taken it a stage further in designing a practical ESR meter. This first part deals with the operation of the circuitry used in the meter.

A lot has appeared in recent issues on the subject of the ESR (equivalent series resistance) of an electrolytic capacitor. The Capacitor Wizard was reviewed by Martin Pickering in June 1998. It's designed to measure a capacitor's ESR in-circuit while ignoring any components that are connected to it. The unit described in this article performs the same task, and a lot of work has been put into achieving the end result. Even if you don't get around to building the meter, this article will give you insight into the design criteria and the way in which the instrument works. But build it if you can: it's effective, very useful and inexpensive.

ESR

In view of Martin's review and also the articles by Ray Porter on a capacitor's ESR (January and April 1993) I won't say a lot about ESR here: it would simply be repetition. To put it in a nutshell, a capacitor's measured ESR (in ohms) is an indication of its 'goodness'. The lower the ohms reading, the better the capacitor. An ESR check can give an early indication of capacitor failure, and is far more useful than a capacitance measurement. Indeed many faulty electrolytic's show OK when checked with a conventional capacitance meter.

In recent months I've talked to many people who don't appreciate the importance of ESR and in what sense it differs from capacitance. So I feel it worthwhile including an extract from a technical bulletin on the Capacitor Wizard written by Doug Jones, the President of Independence Electronics Inc. It sums up the question of ESR well.

"ESR is the dynamic pure resistance of a capacitor to an AC signal. High ESR can cause time-constant problems, capacitor heating, circuit loading, total failure etc. A switch-mode power supply may not start reliably - or start at all. Slight hum bars appear in the video of a VCR or monitor. A TV display may be pulled in from the sides/top/bottom. Diode and transistor failure can occur over a period of time.

These and many other problems are often caused by capacitors with normal capacitance but high ESR, which does not exist as a static quantity and therefore cannot be measured using a conventional capacitance meter or a DC ohmmeter. ESR exists only when alternating current is applied to a capacitor or when a capacitor's dielectric charge is changing state. It can be considered as the total in-phase AC resistance of a capacitor, and includes the DC resistance of the leads, the DC resistance of the connection to the dielectric, the capacitor plate resistance and the in-phase AC resistance of the dielectric material at a *particular frequency* (my italics) and temperature.

The component combination that constitutes ESR can be thought of as a resistor in series with a capacitor: the resistor does not exist as a physical entity, so a direct measurement across the `ESR resistor' is not possible. If, however, a method of correcting for the effects of capacitive reactance is provided, and considering that all resistance's are in phase, the ESR can be calculated and measured using the basic electronics formula E = I x R! This is the basis of the design of the Capacitor Wizard."

Design Criteria

Capacitor manufacturers quote ESR values measured at 100kHz. So this is the test frequency I chose. The impedance of inductors in the micro henries region can be measured at this frequency, enabling the condition of video heads to be gauged - as they wear and the gap deteriorates, their inductance falls.

The Wizard has a buzzer that sounds when the ESR is below 1Ω or so. A capacitor with an ESR of less than about 1Ω is generally considered to be good, so this is a very useful feature in situations where you want to check a number of suspect components - it means that you need refer to the meter only when there's no beep. I've incorporated this facility, but you must bear in mind that a lot of the capacitors in which we are interested have ESR values of less than 0.5Ω when good. More on this later.

I'd like to stress this basic point before going any further: as with the Capacitor Wizard, the meter described in this article doesn't measure a capacitor's microfarads. It simply lets you know if the capacitor is or isn't up to the job. After gaining some practical experience with the meter, you will soon get to know what reading to expect from a good capacitor - taking into account its capacitance and voltage rating. But in any case the reading obtained with a faulty capacitor usually leaves little doubt as to its condition.

The Op-Amp

The circuit uses the basic op-amp as an oscillator, amplifier, detector, voltage-follower and comparator. So it's appropriate to devote some space to a description of the op-amp and its associated circuitry. Incidentally the term 'operational amplifier' relates to its use in analogue computers and appeared in a paper by Ragazzini and others in 1947. The first general-purpose op-amp, with differential inputs and using the familiar triangular symbol for circuit representation, was introduced in 1952 (Model K2-W, by George A. Philbrook Researches Inc.). It's sobering to think that almost forty years ago an early op-amp, the P2, cost $227 - an eighth of the cost of a VW Beetle at that time: now a superior device can be bought for less than a pound.

The op-amp is a high-gain (x100,000 or so) amplifier that usually has two inputs, one non-inverting (labeled +) and the other inverting (labeled -). For practical purposes the gain can be considered as infinitely high, with no current flow at the inputs. The op-amp is designed primarily to operate stably with

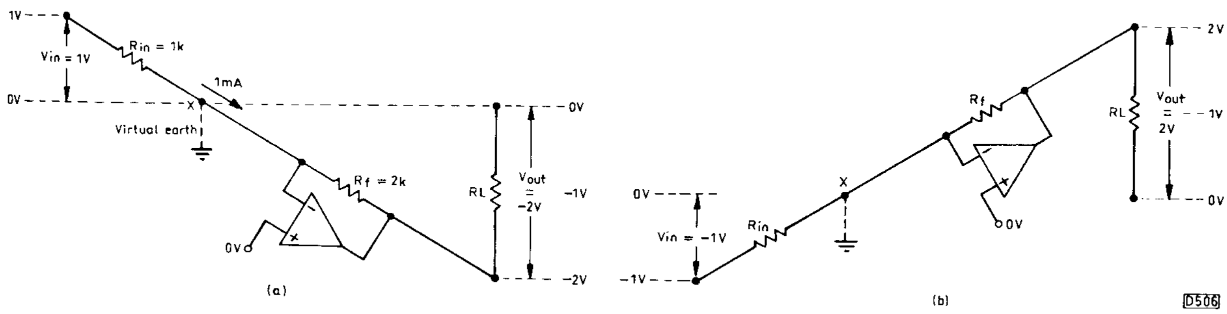


Fig. 1: Precision inverting op-amp circuit, (a) with a positive input, (b) with a negative input. Note how Rf and Rin behave like a seesaw as the input goes from positive to negative, with the pivot at the null (virtual earth) point X. The gain of the stage is

heavy negative feedback. In fact from the historical point of view the op-amp and the concept of negative feedback (the invention of H.S. Black, working for Bell Laboratories, in 1927) are synonymous. Black was working on telephones, his objective being to achieve stable gain independent of the characteristics of a valve (a thermionically-activated FET to youngsters!). When he tried to patent his negative-feedback amplifier in 1928 the idea was ridiculed. Over the years however this concept has become one of the most important in the field of electronics. Marconi had much the same problem. It seems that people often dismiss things they don't understand.

Anyway, I digress. To get back to the point, the op-amp usually requires a positive and a negative supply with respect to a common earth. These supplies are often not shown on circuit diagrams, being taken for granted. The common earth (OV line) serves as a reference point for the voltages that are present in the circuit and as a return path to the power supply for any currents generated by the device's operation.

The main point here is that if the voltage at the + input increases with respect to the voltage at the - input, the output voltage will be positive-going. Conversely if the voltage at the + input decreases with respect to the voltage at the - input the output voltage will be negative-going. Thus in normal practice the output corresponds to the *difference* between the inputs.

If the op-amp doesn't have any negative feedback and the + input is at only 0.1mV above the - input, the output voltage will be close to that of the positive supply rail. If the + input is lower than the - input by the same amount, the output voltage will be close to that of the negative supply rail. Thus the gain is equal to the average slope, which is typically l0V/0.1mV = 100,000. This very sensitive property is used in comparator circuits (it's used in the ESR meter's buzzer circuit). But the op-amp is far more useful when the output is restricted to narrower limits.

The Precision Inverting Amplifier

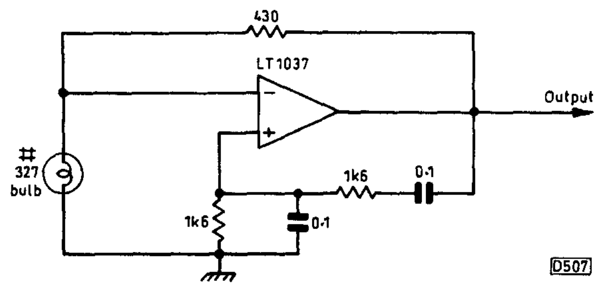


Fig. 2: Jim Williams' original circuit, the first attempt at combining an op-amp with a Wien bridge network to form an oscillator.

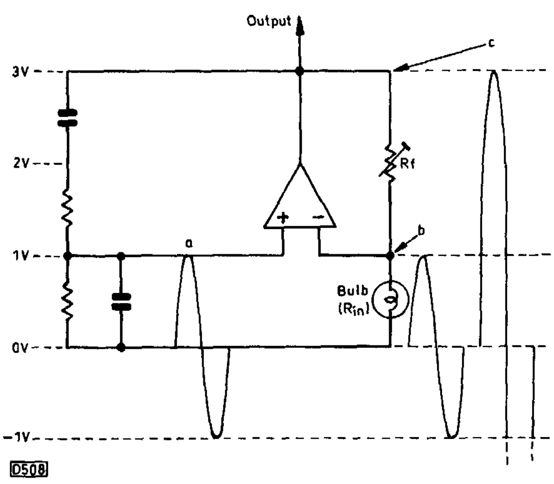


Fig. 3: An op-amp Wien bridge oscillator arrangement with the output set at 6V p-p (positive peak shown). At the resonant frequency points a, b and c are in phase and the waveforms at the op-amp's inputs are a third of that at its output. The ratio Rf/Rin = 2.

This is one of the most common op-amp applications and is used in the second and third stages of the meter. Circuit operation will hopefully be made clear by the rather unusual representation (due to Tom Hornack) shown in Fig. 1.

At (a) the op-amp is arranged to provide a voltage gain of two. The fact that in this case the output is inverted (the gain is minus two) is not important. The heavy negative feedback via resistor Rf forces the output to be such that the voltage at the - input is equal to that at the + input, which is 0V. Remember that the op-amp responds to the *difference* between its inputs. As point X is at earth potential, there is 1V across Rin (1kΩ) and the current flow via Rin, calculated by Ohm's Law, is 1 mA. There is no current flow at the input of the op-amp, so this 1 mA flows via Rf (2kΩ) which thus has 2V across it.

Notice how Rf and Rin behave like a seesaw as the input goes from a positive to a negative value, with the pivot at the null point X. This point is referred to as a virtual earth. There is no current path between point X and earth, and point X is always at zero voltage with respect to earth. The concept of a virtual earth is used as a short-cut when the operation of a current-to-voltage converter is analysed. From Fig. 1 you can see that, because of the virtual earth, Rf appears to be in parallel with RL. So the voltage across Rf appears across the load as the output voltage. But although the null point is considered to be at earth potential, at a microvolt level it's very much active.

It can be seen from Fig. 1 that the stage gain, within the limitations of the supply, is determined by the ratio of Rf to Rin. Incidentally there's a frequency limit on the gain: with common types of op-amp we are limited to a gain of about x10 at 100kHz. If the resistors in Fig. 1 are transposed the stage gain will be 0.5 - the circuit acts as an attenuator.

Overview

Before we go further, it would be as well to provide a quick introduction to the meter circuit presented here (see Fig. 5). The first stage consists of a 100kHz oscillator, whose output is fed to the capacitor being tested. Put simply, the current flow through the capacitor is sensed then amplified as a voltage. It's finally detected and measured by the meter movement.

The better the capacitor, the lower its ESR and the higher the meter indication. It's not quite this simple, because the meter must ignore the other components connected to the capacitor being tested. We'll come to the solution to this problem later.

The Oscillator - History

At the heart of the meter there's a Wien bridge network oscillator. This form of oscillator has an interesting history which is worth a few paragraphs.

In 1939 William Redington Hewlett (co-founder of Hewlett-Packard) produced his Stanford thesis A *New Type Resistance Capacity Oscillator.* It made use of a resonant *RC* network that had been conceived by Max Wien (pronounced Vene) in 1891. The American inventor Lee DeForest (yes, we can blame him) hadn't started the ball rolling yet with the creation, in 1906, of the triode valve. So there had in 1891 been no means of obtaining electronic amplification and Max couldn't have got his network to oscillate. That wouldn't have troubled him, as he was using the network for AC bridge measurement. Amazing what people got up to over 100 years ago, isn't it? I think it was, once again, something to do with telephones.

But Hewlett had the pentode valve at his disposal. He also had Harold S. Black's pioneering work on negative feedback to assist him. In addition there was Nyquist's *Regenerative Theory,* which described the conditions necessary for oscillation.

Hewlett showed that the Wien network could be made to oscillate. A crucial problem had to be resolved however, that of stage gain. With a gain of less than unity there would be no oscillation. With a gain of greater than unity there would be distortion. With unity gain there will be what Hewlett wanted, a sinewave. He had a flash of inspiration: the solution was literally staring him in the face - the electric light bulb.

Hewlett's oscillator was a two-valve affair, with a 6J7 as the oscillator and a 6F6 as the output stage. His solution for gain stability was to wire a tungsten bulb between the cathode of the 6J7 and earth. The negative feedback was applied between the anode of the output valve back to the cathode of the triode oscillator valve. If the output increases for any reason, so does the current flowing through the bulb. As it warms up, its resistance increases. So does the level of negative feedback, thereby stabilising the oscillator's output. Hewlett's idea of employing a light bulb was brilliant in its simplicity. It survived in the HP200 series audio oscillator during a fifty-year production run - into the mid Eighties.

About fifty years after Hewlett built his oscillator Jim Williams, who was working for Linear Technology Corporation, was sitting in his den one rainy Sunday trying to think of something to do. His old HP200 caught his eye. Peering into the back, he saw the light bulb where it had been placed half a century ago, and wondered how Hewlett's oscillator would perform using a modern op-amp. He went on to knock one up - the original circuit is shown in Fig. 2 - and was pleased to find that it had a distortion figure of only 0.0025 per cent.

Perhaps he could improve on it, by eliminating the bulb? Jim was the first to use a JFET in place of the bulb, but with this device the distortion figure rose to a massive 0.15 per cent. Unfortunately there's not space to explain why the use of a JFET gives such inferior results compared to a bulb. In the event Jim discarded the JFET in favour of an optically-driven CdS photocell. This, in conjunction with five op-amps etc., produced an analyser-limited distortion figure of 0.0003 per cent (three parts per million). At one point during his quest Jim writes *(Analogue Circuit Design,* Butterworth-Heinemann) "I could almost hear Hewlett's little light bulb, which worked so well, laughing at me". So no apologies for the use of a light bulb in this design.

Operation of the Oscillator

Fig. 3 shows the Wien bridge network oscillator as you probably won't have seen it drawn before. It illustrates the situation at the peak of the positive-going half cycle. The positive feedback network consists of the series-parallel RC (lead-lag) network: the negative feedback loop consists of the preset Rf and bulb Rin.

We'll consider the RC network first. At very high frequencies the shunt capacitor in the lower arm of the bridge will appear to be a short-circuit and there will be no signal at the op-amp's + input. At very low frequencies the series capacitor will appear to be open-circuit and again there will be no input from the feedback network. At some point in between there will be maximum output from the network. The frequency at which this occurs is equal to $1/(2\pi RC)$, which is called the resonant frequency (ft) of the bridge network. At this point there is no phase shift across the bridge, and the upper arm of the network has twice the impedance of the lower arm, giving a transmission loss of 1/3. To overcome this loss and achieve the required stage gain of unity, the closed-loop voltage gain (ACL), which is set by the ratio of Rf to Rin, must be three. The formula for the closed-loop gain of a non-inverting amplifier is ACL = Rf/Rin + 1, Rf/Rin must be two in order for ACL to equal three.

At power up the negative feedback is low, because the bulb is at its lowest resistance, and the gain is high. As a result oscillation begins immediately, and the bulb is warmed by the current flow. Within a fraction of a second the resultant increase in its resistance reduces the oscillator's output. It settles at the level at which the bulb's resistance is half that of the feedback resistor Rf. So the value of Rf sets the amplitude of the output. Note that the bulb's thermal delay means that it cannot follow oscillations at relatively high frequencies. It responds to the RMS current only, and thus behaves as an ordinary resistor.

The Bulb

Although the Wien bridge oscillator is the accepted standard at frequencies up to say 1 MHz, the use of a bulb for gain control, popular in the USA, has never found favour on this side of the Atlantic. I think I know the reason for this. In most textbooks things begin to get a bit vague when it comes to the actual type of light bulb to use.

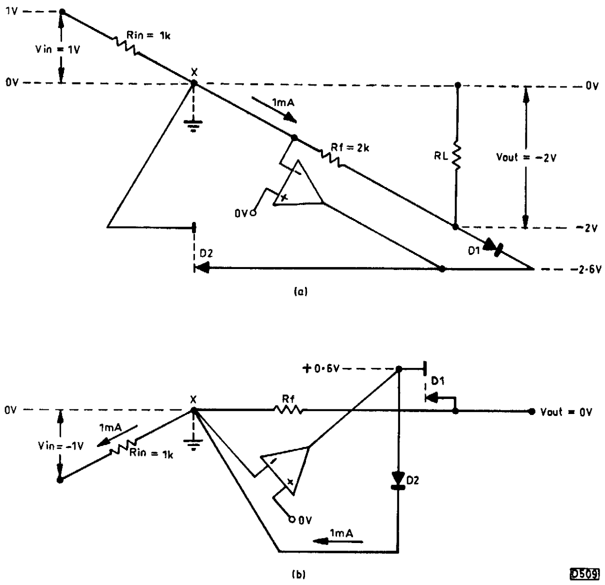


Fig. 4: Precision rectifier circuit, (a) with positive input, (b) with negative input. In (a) the op-amp's output goes as low as required to overcome the forward voltage drop across D1 and still satisfy Ohm's law as far as Rf and Rin are concerned. D2 is off as the voltage at it's anode is 2.6V less than at it's cathode. In (b) D1 is off, it's cathode voltage being 0.6V higher than it's anode voltage. The conduction of D2 limits the positive output at 0.6V. This limiting factor speeds up the recovery of the op-amp when the input goes positive again.

It is often said that any low-voltage, low-current bulb can be used. This is not so. I have seen the following flawed reasoning in some books. Take a 12V, 50mA bulb which has a resistance of 12V/50mA = 240Ω. The feedback resistor must be twice this, i.e. 480Ω or a 1kΩ preset. There's nothing wrong with this value for the feedback resistor, but it won't work with such a bulb. The point that's been missed is this: the bulb must be operated at a current level that gives a large change of resistance.

This occurs when the current is only a few milliamperes, and nowhere near bulb incandescence. What we require is a bulb that has a resistance of about 200Ω *when cold.* When the type of bulb normally specified is used, the result is overloading of the op-amp, distortion, heavy current drain and dependence on the supply voltage for regulation rather than correct bulb operation.

I didn't do what Hewlett did, which was to plot the *IV* characteristics of various bulbs carefully. I simply measured the resistance of bulbs that I thought might be suitable, and found that the cold resistance of a 28V, 24mA bulb is 170Ω. This seemed to be about right. When I tried it - bingo! So when, in this connection, you see "any low-voltage, 50mA or so bulb" you can in future read "a 28V, 24mA bulb". The oscillator will work a treat.

The Precision Rectifier

The final stage of the basic meter uses an op-amp as a precision rectifier. Keeping to the type of representation we've used before, Fig. 4 shows its method of operation. With a conventional rectifier there's the drawback that the signal must rise above the diode's forward voltage drop before conduction begins. This can be overcome by the use of an op-amp in the circuit. At (a) in Fig. 4 the input is positive and the output reduces the voltage at the cathode of Dl. This enables the input to carry on via Rf to the amplifier's output. As in the case of the inverting amplifier circuit, the output is again Vin x Rf/Rin. The diode's forward voltage drop, which is 0.6V with a silicon diode, is overcome because the op-amp's output goes lower by this amount, satisfying Ohm's law as far as Rf and Rin are concerned. Point X is still held at earth potential by feedback action from the output. D2 is off at this time, as the voltage at its anode is lower than that at its cathode. When the input goes negative however, as shown at (b), the op-amp's output rises to

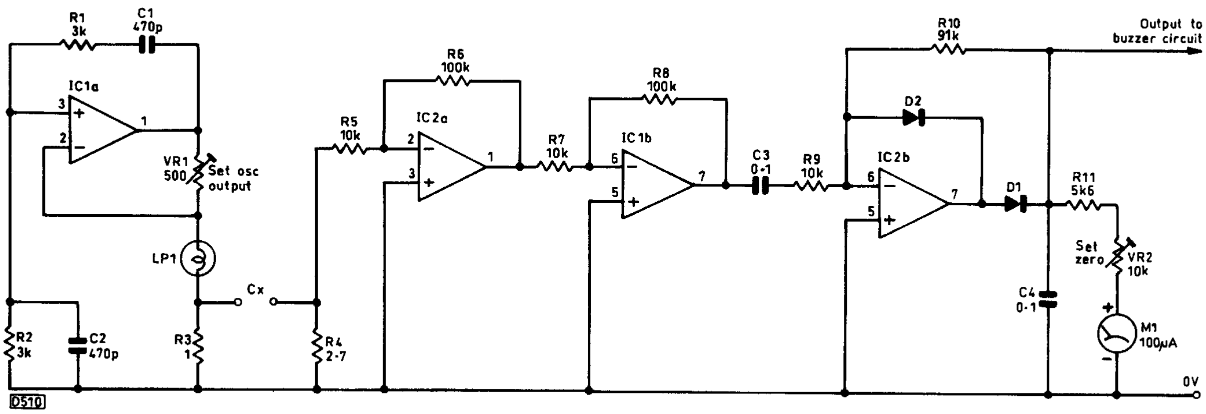


Fig. 5: The basic meter circuit. VR1 sets the oscillator's output level. Pin 8 of IC1 and IC2 is connected to the +ve supply, pin 4 to the -ve supply.

the point at which D2 conducts. The current then flows via Rin, point X and D2. D1 is now off and the output is zero.

Basic Meter Circuit

The circuit of the meter itself is shown in Fig. 5. The Wien bridge oscillator, redrawn, is the same except for the inclusion of a 1Ω resistor (R3) between the bulb and the 0V line. Depending on VR1's setting, the bulb's current is typically 3.5mA RMS. As a result, in the absence of a capacitor under test about 10mV peak-to-peak at 100kHz is developed across R3.

VR1 sets the amplitude of the oscillator's output. In this case the output is used only for feedback, and is set at 5V peak-to-peak. There is nothing magical about this figure, and with this application no test equipment is required to set it. It's just that to get a higher level output you would have to use a higher supply voltage. In fact however the higher the output voltage the better.

The ESR of the capacitor being tested forms part of a potential divider with the 2.7Ω resistor R4. The voltage waveform across this resistor, as a result of the current in the capacitor, is amplified by the rest of the meter circuit. Bear in mind that with the range of ESR values we are measuring an ideal mid-scale figure would be about 3Ω. With low ESR values (good capacitor) the signal across R4 is high, while with a poor capacitor it will be low - often, in relation to 2.7Ω, there can be an effective open-circuit.

Now if, for example, the ESR is 2.7Ω, half the source voltage across R3 would be passed to the meter and a half-scale reading would be expected. It doesn't quite work out like this however, because the source voltage is not independent of the load, and we will be setting full-scale deflection with R3 and R4 in parallel (test leads shorted).

If the ESR tends to go below the value of R4, it becomes more effective in increasing the voltage across R4. As the ESR rises above the value of R4, it becomes less effective at increasing the voltage across R4. Hence the non-linear scale, which is ideal with this application. R3 and R4 are of necessity low in value, because they compare with the values of ESR in which we are interested. The bonus here is that because of their low values the effect of associated in-circuit components becomes insignificant.

The design of this little network is such that the waveforms across R3 and R4 are virtually in-phase regardless of the value of the test capacitor. So we are measuring *the total in-phase AC resistance* to which Doug Jones refers (see quotation earlier).

You might wonder why the test signal amplitude is so small. It isn't because we want to avoid turning on semiconductor devices - we could go up to a couple of hundred millivolts before there would be any worries about that. It's simply a matter of power consumption. Even our little 10mV requires 3.5mA, and in this case I have (dare I claim cleverly?) used a current source that's already there. A 100mV test source would require a hefty, 35mA, quite a drain on resources. If anything the value of the 1Ω resistor could be even lower, so that with respect to 2.7Ω it would more closely approximate a constant-voltage source.

You may think that to test an electrolytic capacitor effectively a fair old current should be pumped through it. Not so. A healthy 1,000uF capacitor will still present 0.05Ω or so to a couple of millivolts and thus be able to produce a reading.

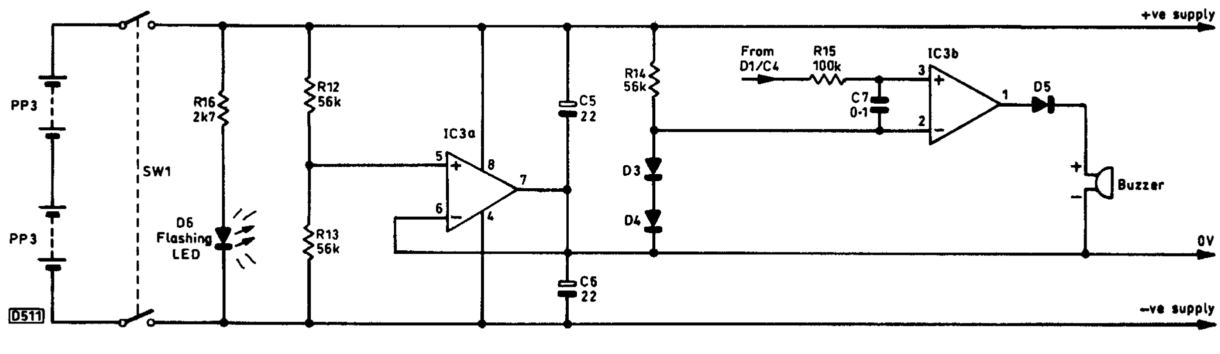
The signal across R4 passes through two stages of amplification each with a gain of ten, and is then detected for the meter movement. There is further amplification in the detector stage. The output is integrated by C4 to produce a DC output of about 1.3V with the test leads shorted - this corresponds to zero ESR.

The basic meter circuit uses two dual op-amps. You will see that the signal path from the oscillator in ICI passes to IC2 then back again. This is done to prevent the first, sensitive stage of amplification picking up a strong oscillator signal in the same package.

The Power Supply

There is no need for a regulated supply, because the bulb stabilises the oscillator and the amplification factor of the op-amps is fixed by the ratio of the feedback and input resistors.

The power supply arrangement used is shown in Fig. 6. IC3a generates split rails from a single supply line. The voltage at its output pin 7 is at half the supply voltage, because the voltage at its - input (pin 6) is equal to the half-voltage level set by R12 and R13 at its + input (pin 5). This way of using an op-amp is



known as the voltage-follower. There is total negative feedback, and the closed-loop gain is unity.

The meter's total current requirement is only some 10mA, plus a couple of mA for the on indicator D6. Two PP3 batteries in series are ideal. Long life is assured - if the oscillator's output is set as described later, the meter's accuracy will be maintained until the supply drops to about 5V per battery.

If the link between the batteries was connected to the 0V rail this split-rail arrangement would be unnecessary. It's included to enable a DC adaptor to be used as an alternative power source. An adaptor with an output from 12V to 30V can be used. A regulated type is best, as ripple on the supply could cause problems.

The Buzzer

IC3b serves as a comparator for buzzer operation. The output from the meter rectifier circuit, across C4, is applied to the + input (pin 3) for comparison with the voltage at the - input (pin 2). If the voltage at pin 3 exceeds that at pin 2, the output at pin 1 goes high (see comparator circuit description earlier) and the buzzer sounds. About 1V is developed across the series-connected diodes D3 and D4. When the ESR value of the capacitor being tested is about 1Ω or less, the voltage across C4 rises above this 1V reference.

Next Month

In Part 2 next month we will deal with construction, setting up, use and inductance measurement, and in addition provide a bit more information on ESR. A detailed components list will be included.

Design of an ESR Meter

In this second part Alan Willcox deals with construction and setting up of the meter, upgrades and use, and provides additional background information

In part 1 last month the design criteria were specified and a full description of the operation of the circuit was provided. The meter is simple to build and the effort required is well worthwhile.

Construction

Fig. 8 shows the board layout. For convenience, 0.1in. matrix stripboard is used. The most common problem concerns the print cuts. If these are made by twisting a drill bit by hand, as I do, instead of using the correct tool, it's all too easy for the cut to be incomplete or for some of the print to spread over to an adjacent track.

If a double-pole on/off switch is used, this is a convenient point for the connection of an on/off indicator. A flashing LED with a 10kΩ series resistor does the job well: although it takes only a couple of mA, the flashing light does catch your eye.

It is best to use screened cable for the test leads, in order to avoid pick-up of unwanted radiation from any working TV line output stage in the vicinity. Rather than use plugs and sockets, solder the test leads to the PCB , we are often concerned with ESR values of less than 0.1Ω, and it doesn't take long for a plug-and-socket connection to deteriorate and produce resistance values greater than this. The length of the leads is not at all critical. I use a 24in. length of screened audio lead terminated by two 8in. lengths of flexible wire.

On a cold, frosty morning, before the workshop has reached its normal comfortable, cosy (?) temperature the meter's readings may increase slightly. Although this increase may amount to the equivalent of less than 0.1Ω, the fact that accurate low-resistance readings are often required justifies the use of an off-the-board set-zero control rather than a preset type as used in the Wizard ESR meter.

This control also comes in handy if you want to squeeze the last ounce out of the batteries, but the buzzer can't be relied on when the batteries produce less than 5V and the output from the oscillator begins to fall. Also useful in this respect is the ability to alter the pointer position easily at maximum output, to be able to observe the operation of the bulb and the correct functioning of the oscillator. This is covered in the set-up notes later.

Probe clips were used for the all-important probes. The hooks were cut off, the internal springs were removed, then the plastic was cut back to expose more of the probes. They have proved to be ideal in practice, and small enough to often be able to get under the capacitor on the component side of the PCB. The probes are not polarity conscious, and it doesn't matter which connection is used for the screen of the test lead.

The suggested board size (3 x 2in.) is slightly larger than it needs to be to accommodate the components. There are two reasons for this. First, so that it will slot into the case that was selected, and secondly to allow space for future upgrades. With this in mind the set-zero control is offset to the right, allowing space for a modular preset shaft.

The batteries are secured with self-adhesive Velcro. It's a simple solution, and the Velcro will transfer several times.

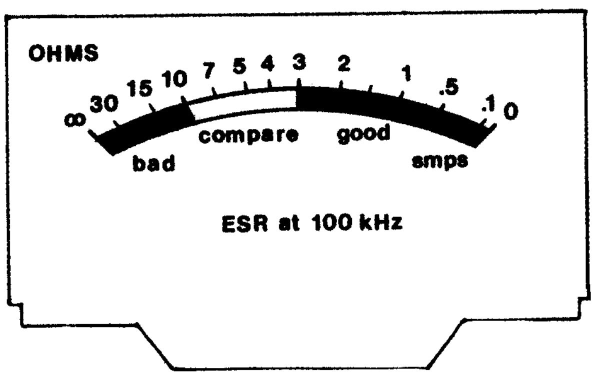


Fig. 7: Suitable meter scale, reproduced full size.

Upgrades

The first upgrade, which will be described in a following issue of the magazine, arose from feedback within the trade. In common with the Wizard this meter does not differentiate-between a short-circuit capacitor and a really good one (with an ESR around 0.05Ω). Now although we all know that a short-circuit electrolytic capacitor is quite rare, it can occur and has caught me and others out. A lot of time can be wasted when it occurs and is missed. So I've been testing an addition that gives an audible indication when a short-circuit is present. A further refinement is an auto power-off facility.

I've not included these extras at present because I feel it best to present as simple and economic a project as possible initially. But space has been left for these additions.

Component Sources

I obtained most of the parts used in the prototype from Maplin Electronics and have included this company's part numbers in the components list. The buzzer and meter movement were obtained from CPC. For correct operation of the oscillator it's vital that C1 and C2 are good-quality polystyrene capacitors.

Apart from the bulb, the specification of the other components is not critical.

The Meter Scale

The geometry of the meter's scale (see Fig. 7) is dictated by the relative values of R3 and R4. If the value of R4 was increased to say 10Ω, this would be the midscale reading and R3, being low in comparison, would have less effect. Say a capacitor with an ESR of 10Ω is connected. Half the signal across R3 will be passed on, and little of its current will be diverted to reduce R3's voltage, which is the result of the current through the bulb. A mid-scale reading of this order may be more appropriate for testing surface-mounted electrolytic capacitors, which seem to have higher ESR values. I have no data on this type of capacitor at the time of writing however.

Anyway, the value of R4 used here, 2.7Ω, does affect the source voltage to an extent that has to be considered. The current that flows through the bulb is controlled by the setting of VR1. R3, being only 1Ω, does not affect the operation of the oscillator.

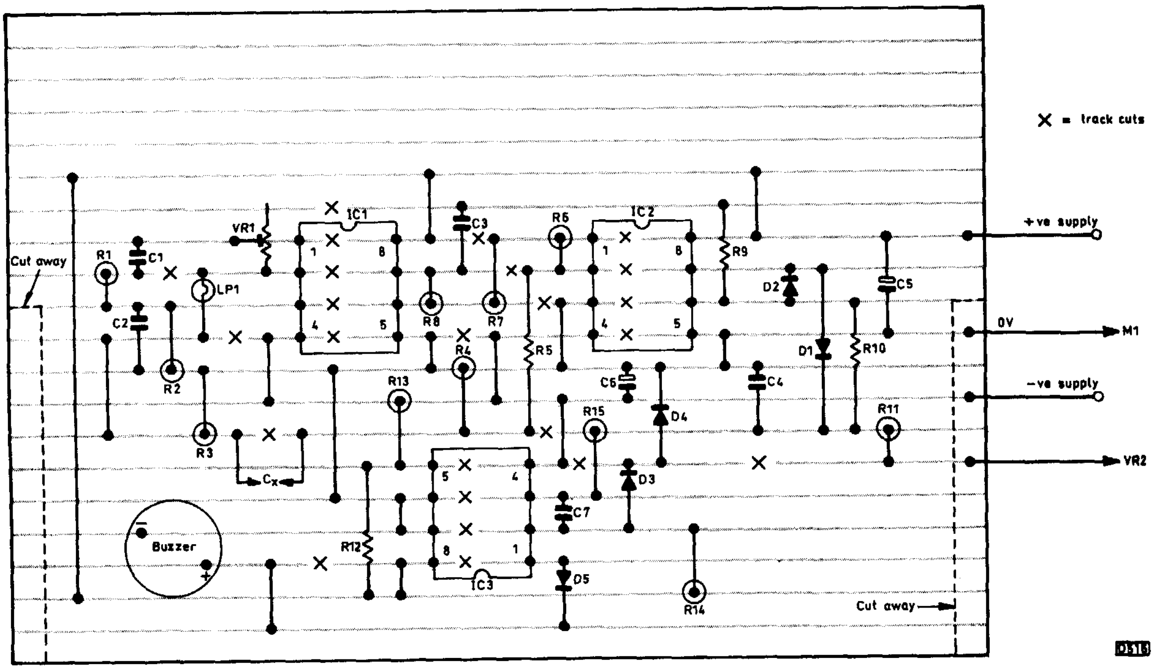
Scale calibration with an 0-100 dial ideally follows the rule

Reading = (R3 + R4)/(R3 + R4 + ESR) x 100.

In practice the signal becomes so low at high ESR values that some non-linearity in the circuit is apparent, the result being a slight departure from this formula. Because of this, it's better to use either fixed resistors to calibrate the scale or copy Fig. 7. If a standard 90° movement of a different size is used, it is easy enough to reduce or enlarge the scale by photocopying.

Setting Up

The first consideration is the oscillator's output level. With the specified lamp, the oscillator will work down to 2V peak-to-peak. But bear in mind that the oscillator's output setting is not important in itself - full-scale deflection is simply adjusted by VR2 with the test leads shorted together. Low setting of the oscillator's output provides a longer battery life, reducing the level at which the bulb ceases to function as a regulator. The test signal can however be so low at high ESR values that accuracy



suffers. In practice an oscillator output of about 5V peak-to-peak is a good compromise.

If an oscilloscope is not available, the following simple method can be used. Connect a 1Ω resistor between the test leads and turn the set-zero control VR2 (shown incorrectly as a preset in Fig. 5 last month) anticlockwise. Advance the setting of VR1 slowly. Just after the half way point the oscillator will start up and the meter's pointer will deflect. Carry on until the buzzer sounds steadily. At this point the oscillator's output should be close to 5V peak-to-peak. Note that with each adjustment the pointer will twitch briefly as the bulb settles, giving the impression that the potentiometer is noisy.

Leave the set-zero control at minimum and observe the operation of the bulb by switching on with the probes shorted together. You will see the pointer deflect high then almost immediately jump down to the stabilised position.

Once the oscillator's output has been set, adjust VR2 for full-scale deflection with the probes shorted together. Finally, centre the control knob.

Using the Meter

Experience with the meter provides the best guide as to what ESR value to expect of a good capacitor. Some general guidelines can be given however. The reservoir and smoothing capacitors on the secondary side of a chopper power supply should all give readings of less than 0.5Ω. A practical ESR limit is 0.05Ω. With an electrolytic capacitor of 100uF or over value, you should expect a reading close to this and certainly below 0.5Ω.

There are some exceptions however. I'll mention them here as they can cause confusion. A high ESR value is to be expected with IuF high-voltage electrolytics: if the meter deflects at all, the capacitor is often OK. This type of capacitor is widely used as a start-up component. Being operated in a DC context, its ESR is less important. As an example a new 450V type may well produce a reading of the order of 30Ω. At the other end of the range you get the l,000uF, low-voltage type. If one of these doesn't produce a reading of 0.lΩ or less it's duff.

Table 1, from Dubilier, provides a useful guide. In addition, if you are unsure what reading to expect it's easy enough to make a comparison with a similar type from your well-stocked tray of electrolytics.

The meter has good protection against placing the probes across a charged capacitor, but this should of course be avoided. The only real cause for concern is the `main smoothing block', i.e. a mains bridge rectifier's reservoir capacitor. We all know that this capacitor can deliver a hefty punch when a power supply has failed to start up. If you are of the type with a tendency to such accidents, it would be prudent to wire a couple of beefy diodes back-to-back across the meter's input. This should protect the meter, but it won't help your heart - or your probes - in the event of such a misfortune. It's good practice to discharge this capacitor with a mains-type bulb - it is always reassuring to have a visual indication that little charge remains. See warning note later.

Inductance

As the meter operates at 100KHz, any inductance in the circuit under test becomes significant. The loudspeaker that reads 8Ω on your conventional ohmmeter appears to be nearly open-circuit with the ESR meter.

This property can be quite useful. When testing a line output stage for example you might find that there's a short-circuit across the transistor. In this event there are in general three possibilities, (a) the transistor is short-circuit, (b) the line output transformer has a primary-to-secondary short, or (c) the HT line has a short-circuit across it. If the short-circuit is still present when the ESR meter is used, the transistor is almost certainly the culprit: in the other two cases the ESR meter will give an open-circuit reading because of the inductance of the transformer's primary winding.

Video head testers operate by measuring, in effect, the inductance of the head. Its impedance falls as the gap deteriorates with wear. Although this meter operates at a frequency that's inappropriate for a video head, it can give a relative indication of the head's condition. I don't have a collection of heads in various states of health to be able to confirm any figures, but it seems that new heads produce a reading of about 2 Ω while worn heads produce a reading of about 1Ω.

Inductors with millihenry values, of the type used in EW modulator circuits, normally give an open-circuit reading. But if a shorted turn is present the inductance drops dramatically and the meter's pointer will deflect.

Analogue v Digital

In dealing with the problem of in-circuit ESR measurement I've used traditional analogue technology. But, as is often the case, there's another way of doing things. Bob Parker, an engineer `down under' who was convinced of the importance of such an instrument, first tried analogue circuitry. After "a few fairly unsuccessful attempts" he opted for a digital approach. His solution is to use a Zilog processor with, instead of a sinewave as a test signal, short current pulses applied to the capacitor being tested. The resultant voltage pulses, which are proportional to the electrolytic's ESR, are compared to the level existing on a ramp generator. Time measurement by the Z86 processor determines the amplitude of the pulses.

As far as the power requirement is concerned, there's a parallel in the form of a remote-control handset. The LED is pulsed with a high current for a short period, the average current drawn being low. The brief high current is supplied by a reservoir of stored power in an electrolytic capacitor that's wired across the battery's connections.

Friendly rivalry between the analogue and digital camps has existed for a long time. This brings to mind an old story that sums it up well. Two male engineers, one specialising in digital design and the other in analogue design, are working together in a lab. A nude female appears at the door, attracting the attention of both men. This vision of beauty announces that every ten seconds she will reduce the distance between herself and the engineers by one half. The digital engineer looks disappointed and cries "that's terrible, she'll never get here". The analogue engineer smiles and then replies "that's OK, she'll get close enough".

More on ESR

Bob Parker (*Electronics Australia*, February 1996) puts it this way.

"The electrolyte has an electrical resistance which, along with the (negligible) resistance of the connecting leads and aluminium foil, forms the capacitor's equivalent series resistance. Normally the ESR has a very low value, which stays that way for many years unless the rubber seal is defective. Then the electrolyte's water gradually dries out and the ESR creeps up with time. The electro gradually comes to act like a capacitor with its own internal series resistor . . . Heat makes it worse. If an electro is subjected to high temperatures, especially from heat generated internally as a result of large ripple currents, the electrolyte will start to decompose and the dielectric may deteriorate - the ESR will then increase far more rapidly. To make things worse, as the ESR increases so does the internal heating produced by the ripple current. This can lead to an upward spiral in the capacitor's core temperature, followed by complete failure -sometimes even explosive . . ."

Table 1: Typical ESR values at 100KHz

Capacitance value	*Voltage rating*	*Impedance**
1uF	50V	4Ω
2.2uF	50V	2.8Ω
4.7uF	50V	2.4Ω
10uF	63V	1.9Ω
22uF	50V	1.3Ω
47uF	25V	1.3Ω
47uF	50V	0.7Ω
100uF	16V	0.5Ω
100uF	35V	0.25Ω
220uF	16V	0.25Ω
220uF	35V	0.114Ω
470uF	16V	0.114Ω
470uF	35V	0.065Ω
1,000uF	16V	0.065Ω
1,000uF	25V	0.041Ω
2,200uF	25V	0.036Ω
2,200uF	35V	0.034Ω

*When new - low-ESR type.

Both Bob (Dick Smith Electronics) and Ray Porter, in an article on ESR meter design in this magazine a few years back, mention the use of fixed resistors to assist with meter calibration. Armed with this information, and considering the fact that ESR is an in-phase component, I have made the assumption in my calculations that ESR amounts to the same thing as an equivalent fixed resistor.

Other uses for the meter emerge the more it is used. For example, non-electrolytic capacitors can be measured and their capacitance estimated. But because of the different types of capacitor construction in use, I can't come up with any hard and fast rule. A lower limit for measurement is about 0.1uF. There seems to be less and less need these days to measure the actual value of a capacitor. With line output stage tuning capacitors and timing components a conventional capacitance meter is more appropriate.

The ESR meter is one of those things that, once you have one, you wonder how you ever managed without it. Hats off to whoever came up with the idea - it's not mine. I've just taken this opportunity to share with you the course I adopted to end up with the solution presented here. I haven't clapped eyes on the Wizard yet - we can't afford one down here in Wales. I'd like to know how the Wizard designer approached the problem, but no information has come my way.

The idea for my meter was triggered off by the Wizard. When I first read about it I was impressed. It would test that most troublesome of all components, the electrolytic capacitor. Not only that but it would do so in-circuit, ignoring associated components. I liked the idea of a conventional meter movement with its easy-to-interpret scale, also the buzzer feature for quick checking. But the meter was shrouded in mystery and its price tag was beyond me. So I decided to have a go myself.

Development

A clear picture formed in my mind as to how to go about it. My idea was to supply a low-value resistor (10Ω) with a constant-current 100kHz sinewave, amplify and rectify the resultant voltage waveform across this resistor and feed it to a meter movement. In this situation the meter is to be set at full-scale deflection. The test leads were to be connected across the resistor. Now if the capacitor being tested has an ESR of say 10Ω, the voltage across the resistor would fall by half. Thus half-scale deflection would correspond to an ESR of l0Ω and so on. A very low ESR (good capacitor) would produce a near-zero reading while a poor capacitor would have little effect, the pointer remaining at near fullscale deflection. The result is a meter scale in opposite sense to that of the Wizard.

Within a couple of months of the start of development work on the project I had a working prototype and decided to write an article about it. Then, at the eleventh hour, I had second thoughts. Something was nagging me. The meter looked OK, did its job, and others were happy with it. But after using it for some time I felt that something was not quite right.

My main concern was that it seemed to be very sensitive to the inductance of the test leads. This impedance meant that even with the test leads shorted the reading could not be brought down to zero. I had introduced measures to offset this, but in this connection a more serious problem emerged after some further use.

When a capacitor with a very low (near zero) ESR was being measured, the pointer would vary about the zero point if the distance between the test leads was altered. If they were close together, their inductance would tend to cancel and the reading would decrease. I was aware how important it was to be able to differentiate between say 0.5Ω and 0.1Ω or between 0.1Ω and zero. This was a design weakness, and I was not happy.

At this time Bob Parker's K7204 ESR meter became available. I had one with which I could make a comparison, and noticed the same sensitivity to inductance that I was experiencing. Both meters monitor the voltage across the capacitor, whereas the Wizard measures the current through the capacitor - this was clear from its scale.

I went on to build a little circuit to do just that and, lo and behold, this over-sensitivity disappeared. The effective lead impedance dropped dramatically, and that which remained could be simply compensated for by means of the FSD preset. So it seemed that the Wizard way was the right way. All this can be explained using the relevant maths, but I'm not about to brush up on my theory and extend this article longer than it is already.

Reluctantly, I accepted that I had to scrap my original idea and start all over again. This was by now becoming an obsession with me - I had to come up with the best solution, and it had to be the simplest.

Certain things had to go. After some use I realised that plugs and sockets for the test leads were out of the question. Their increasing contact resistance made low-ohms readings unreliable. I had also been determined that the meter should operate with a single PP3 battery.

To this end I had built a DC-DC converter to provide a negative supply line. This provided operation down to 7V. But it used 7mA and greatly increased the circuit complexity. To do away with it meant that I needed a higher supply voltage. The use of two PP3s in series to obtain this may seem to be a backwards step, but isn't really. The meter now takes half the current used by the first prototype, and will regulate down to less than 5V per battery. In fact the meter reading remains unchanged over the supply range 10-30V with the oscillator set at 5V peak-to-peak.

Now, almost a year after building my first prototype and quite a few versions later, I have presented this - my final (?) solution!

Warning

It seems that forgetting to discharge the main smoothing block or HT reservoir capacitor before measurement is a more frequent occurrence than had been expected. When this happens R4 at least will blow. As replacing components on stripboard is a messy job, I strongly recommend that protection is built in. A small board with two 1N4007 diodes wired back-to-back and a 1A (N25) circuit protector in series with one of the test leads can be mounted on the back of' the meter movement.

Thanks

I have to thank Martin Pickering for his constructive comments after testing an earlier, voltage-sensing prototype meter.

Components list

Item	Value/type	Order code
R1, R2	3kΩ, 1%	M3K
R3	1Ω	M1R
R4	2.7Ω	M2R7
R5, R7, R9	10kΩ	M10K
R6, R8, R15	100kΩ	M100K
R10	9kΩ	M91K
R11	5.6kΩ	M5K6
R12, R13, R14	56kΩ	M56K
R16	2.7kΩ or 10kΩ	M2K7 or M10K
VR1	500Ω cermet preset	WR39
VR2	10kΩ linear potentiometer	JM71

*Value for current economy

Item	Value/type	Order code
C1, C2	470pF, 1% polystyrene	BX53
C3, C4, C7	0.1uF miniature resin dipped	RA49
C5, C6	22nF, 16V	VH09
IC1, IC2, IC3	TL082CN	RA71
D1, D2, D3, D4, D5	1N4148	QL80
D6	Flashing LED plus clip	QY96 and YY40
LP1	Miniature wire-ended 28V, 24mA lamp	BT44
M1	100uA meter movement	CPC code PM 11125
SW1	DPST switch	RD17
Buzzer	Miniature alarm	CPC code LS-M3
Stripboard		JP47
Case	ABS box type BM22	CC83
Knob		YX01
Batteries	Two PP3s plus clips	HF28
Probe clips		HF21

Order codes are Maplin's unless otherwise indicated.