In this two-part article, Cyril Bateman reveals how to analyse capacitors with a view to detecting and preventing failures.

Understanding capacitor

When I first started to learn about capacitors, my engineering manager's favourite instruction was, "Measure to gain understanding." This dictum remains just as true today, despite improvements in both equipment and capacitor manufacture.

With many new capacitor product ranges continuously being introduced, and rather fewer ranges becoming obsolete, most component catalogues now omit various performance characteristics. And many main-stream component distributors no longer sell capacitor makers' data books.

Over-stressed or miss-applied capacitors are directly or indirectly involved in most circuit failures. All components deteriorate with time, but miss-applied capacitors can fail extremely quickly. Worse still, before a capacitor fails, it can directly contribute to semiconductor failures, masking the prime failure mechanism.[1]

Fig. 1. Vector representation of the interaction between the inductive, X_l and capacitive, X_c reactances which determine measured capacitance value. As the series resistive term R increases, so does the tangent of the angle 'δ' called tanδ, increasing the magnitude of impedance, |Z| but capacitance remains unchanged.

Manufacturers' measurements

Makers' measurements comprise two main categories. Some measurements are applied to every capacitor produced while others are periodic or qualification measurements for national and international approval ratification.

All capacitor production is tested 100% for four major characteristics – capacitance, dissipation factor, voltage proof and leakage current. Regular quality samples will subjected to additional inspections.

End-of-production tests will be supplemented by in-line quality inspections of samples, both electrical and physical, at each manufacturing stage. The results are analysed as part of a statistical process control to optimise yield.

When a manufacturer has gained formal approval to a national or international standard, a program of additional periodic destructive tests, required to maintain this approval, will be agreed. Many makers explain these test requirements in their data books. If you need more information, copies of the specifications can be obtained through national quality supervision bodies.

Table 1. Clear demonstration of how esr changes significantly with frequency. Measured results of a high quality 10 nF polystyrene foil/film capacitor using a Wayne Kerr 6425 precision component analyser.

Frequency (Hz)	C (nF)	Tanδ	Q	esr (Ω)
100	9.9982	0.00010	9000	17.0
1k	9.9988	0.00005	20000	0.80
10k	9.9986	0.00015	6000	0.26
100k	10.000	0.0005	3000	0.05

Supplementary measurements, of interest both to the capacitor maker and circuit designer, will also be performed. Being outside the formal performance claims though, these results will be classified as 'typical'. Such 'typical' measurements centre on measuring capacitance and equivalent series resistance or esr under various conditions or frequencies.

What is ESR?

Having neither resistance nor self inductance, a perfect, loss-free capacitor sustains a voltage in quadrature with the applied current. Analysed on a polar display, voltage would be at –90° and current 0°, so the complementary phase angle δ would be zero. Having no resistive element, this perfect capacitor cannot lose or dissipate energy.[1]

Any self inductance results in a voltage at +90° which subtracts magnitude from the capacitive vector, increasing the apparent capacitance value which is measured.

All practical capacitors exhibit resistance which, appearing in series with the capacitive reactance, degrades this –90° angle to a lesser value, increasing the complementary angle δ. This change of phase angle represents the resistive element which will dissipate energy as heat in the capacitor.

With capacitors, it is usual to refer only to the delta loss angle, described as tanδ, **Fig. 1**.

The resistance acting in series with the capacitor's reactance is called esr. It is the net sum of actual series resistances and any parallel leakage resistances converted to their series equivalents. This leads to the mathematical description of a capacitor's impedance, **Fig. 1**, as,

$$|Z| = R \pm jX,$$

where,

$$jX = j(X_c - X_l)$$

$$X_c = \frac{1}{2\pi fC}$$

$$X_l = 2\pi fL$$

$$\tan\delta = abs\frac{R}{X}$$

$$\theta = \tan^{-1}\frac{X}{R}$$

A near ideal capacitor would have a phase angle, hence tanδ, that remained constant with frequency. Since by definition a capacitor's reactance X_c is totally frequency dependent, so also must be the capacitor's equivalent series resistance, **Table 1**.

These frequency dependent effects can be summarised[1] into the general equivalent circuit of a capacitor, **Fig. 2**.

Any alternating current passing through the capacitor, reacts with this esr, dissipating power as heat and the capacitor temperature rises. Heat increases capacitor leakage current which, according to Arrhenius's law, roughly doubles or halves for each 10°C increase.

Increased temperature, both ambient and self heating, reduces a capacitor's useful life. Additionally every capacitor has a safe internal 'hot-spot' temperature which must not be exceeded.

Measurement of this temperature rise provides a direct correlation between capacitor esr and capacitor through current. There's more on this in the panel entitled Temperature rise.

Temperature rise

When subjected to current flow, the esr of a capacitor causes its temperature to rise. With simple, repetitive waveforms, given the capacitor's esr by frequency data, calculation of power dissipation is straightforward.

With many complex waveforms though, the only reliable method to ascertain acceptable power dissipation might be direct measurement of temperature rise with the capacitor in circuit.[5]

With physically large electrolytic capacitors, measurement of temperature rise is a simple task, easily performed using a small diameter wire thermocouple in contact with the base of the aluminium capacitor case.

With small surface mounted components, measurement of temperature rise is very difficult. Depending on the printed board used, whether single sided, double sided, proximity of other components and or tracks, often makes assessment of temperature rise either inaccurate or impossible.

While infra-red measurements of temperature might be possible, physically small components require an expensive instrument having telescopic, or macro object lenses.

Thermochromic inks are available with suitable temperature ranges, but unless the component has been pre-coated with a black ink, identification of the many colour temperature bands is difficult. Coating a small component with black ink, changes its infra-red emissivity and thus its temperature rise, introducing significant errors.

While the thermocouple approach can be used, with small components, even the thinnest available leadout wires conduct significant heat at elevated temperatures, reducing the component's temperature rise.

One method I have used successfully combines using thermochromic ink with a thermocouple. With constant power applied to the test component, thermochromic ink can be used to determine component temperature reduction when a thermocouple is attached. Subsequent thermocouple-only measurements, can then be corrected for this loss, giving improved accuracy of the measured temperature.

Measuring capacitance and esr

Many excellent and precise *LCR* meters are now available. These are detailed later. Unfortunately though, such equipment is not usually available on rental.

This article presents measurement methods available using commercially available equipment, as well as lower accuracy, lower cost methods. For brevity, I will concentrate principally on measuring capacitance and esr, since all other desired parameters can then be easily calculated. See the panel entitled Conversions and equations.

Traditionally, all capacitor measurements made by an 'approved' manufacturer have been monitored by independent inspection engineers, either from national standards institutes or the defence quality assurance boards. While these bodies monitored products destined for 'release certification', in practice, identical standards were applied to all products.

Twenty years ago, provided the inherent accuracy of the measuring instrument used was at least a factor of ten better than that claimed for the capacitor, the measured values were accepted. Using the best precision bridges then available, capacitance could be measured to this accuracy. But loss factor of the better COG ceramics, low-loss glass, porcelain, polypropylene and polystyrene capacitors could not.

Since then the accuracy of the best *LCR* meters has improved dramatically, especially for loss factor measurement. See the panel entitled Capacitor test instruments.

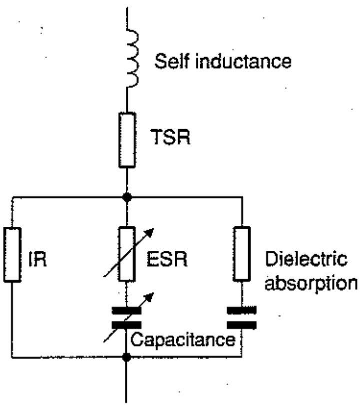

Fig. 2. General equivalent circuit applicable to all capacitors at small signal levels, up to the series resonant frequency. Note however at larger signal levels, as described in the June issue, an enhanced circuit should be applied to electrolytic capacitors.

Insetting results. Formal approvals require measured values for capacitance and loss factor to be traceable to national standards. This means that the equipment used must be maintained in a calibration system. Test limits used must be 'inset' from those actually claimed for the product. This means that the inaccuracy or uncertainty of the measurement instrument and any test leads or jigging used is taken into account.

Test frequencies and voltages. Traditionally, capacitance and loss factor of electrolytic capacitors was measured at 100Hz. All other capacitor types were measured at 1kHz, except for low capacitance values, which were measured at higher frequencies, usually 100kHz or 1MHz. Before pocket calculators were common, 1592Hz was often substituted for the 1kHz measurements, making ω approximately equal to10000 to simplify calculations.

Similarly, the ac test voltage applied to the capacitor being measured has also become standardised. For example, IEC 68-1 for plastic film capacitors specifies a test voltage of 0.03 times the capacitor's rated voltage should be used, subject to an overriding maximum of 5V.

Ceramic capacitors are treated differently. They should first be pre-conditioned by heating to de-age the dielectric, then allowed to stand for 24 hours at standard atmospheric conditions. Measured values, made using an ac test voltage of a volt or less are then adjusted to the '1000-hour value' by applying the appropriate ageing factor.

Aluminium electrolytic capacitors are usually measured at 0.5 volts or less at 100Hz. Obviously, with large capacitance values, considerable generator current may be needed to develop 0.5V, so a much lower test voltage may be needed.

While loss factor is usually specified as tanδ, esr or equivalent series resistance provides an easier insight into a capacitor's performance – especially power handling limitations.

Since both capacitance and tanδ or esr are frequency dependent, maker's test frequencies and voltages should be

Conversions and equations

Subject to an ac voltage, an ideal capacitor resists or impedes the passage of current according to its reactance value,

$$X_c = \frac{1}{2\pi fC}$$

developing a voltage which lags the current by 90°.

In practice, every capacitor has a resistive component. Expressed using conventional series equivalent notation, this resistance further impedes the passage of current.

$$|Z| = \sqrt{R^2 + X_c^2}$$

Each practical capacitor also includes an inductive element, which incorporated in the above provides the full equation for impedance, Fig. 1,

$$|Z| = \sqrt{R^2 + (X_c - X_l)^2}$$

where,

$$X_c = \frac{1}{2\pi fC}$$

$$X_l = 2\pi fL$$

At any frequency the term $X_c - X_l$ can be simplified into its series equivalent $\mathbf{jX_s}$ giving the vector equation $Z = R_s \pm jX_s$. This results in the magnitude/angle expressions

$$|Z| = \sqrt{R_s^2 + X_s^2}$$

$$\angle\theta = \tan^{-1}\frac{X_s}{R_s}$$

In the above expressions, the R_s term represents the equivalent series resistance of the capacitor, while the X_s term represents the series reactive component. When viewed as a vector diagram, a polar plot, or on a Smith chart, this X_s term has a negative value for capacitors, Fig. 1.

The commonly used expressions

$$C = \frac{-1}{2\pi fX_s}$$

and,

$$\tan\delta = \text{abs}\frac{R_s}{X_s}$$

also apply.

While the above series equivalent expressions are the most helpful for larger capacitance values, many *LCR* meters default to the equivalent parallel expressions when measuring small capacitance values. Conversion between series and parallel values is simply performed.

$$R_p = \frac{R_s^2 + X_s^2}{R_s}$$

and,

$$X_p = \frac{R_s^2 + X_s^2}{X_s}$$

One benefit of parallel values is to express them in the form of admittance and susceptances, particularly helpful when calculating combinations of networks in parallel.

$$Y = \frac{1}{R_p \pm jX_p} = Gp \pm jB_p$$

$$G_p = \frac{R_s}{R_s^2 + X_s^2}$$

and,

$$B_p = \frac{X_s}{R_s^2 + X_s^2}$$

The conversion from parallel impedance back to series impedance format is equally simple:

$$R_s = \frac{R_p \times X_p^2}{R_p^2 + X_p^2}$$

and,

$$X_s = \frac{R_p^2 \times X_p}{R_p^2 + X_p^2}$$

applied for all subsequent correlation measurements.

To understand why these different frequencies were chosen, consider some measured values. A typical 10 000µF power supply electrolytic at 100Hz has an impedance of 150mΩ and esr of 11mΩ. At 1kHz, its impedance reduces to less than 20mΩ and esr to 10mΩ.

This 1kHz impedance and esr may be less than the impedance of many test leads or jigs. At higher frequencies, the capacitor's esr dominates the measured impedance, increasing measurement difficulties.

The impedance of a 0.1µF foil and polypropylene capacitor at 100Hz would exceed 15kΩ but its esr would be only 2Ω – a most difficult combination to measure and one subject to noise pickup. At 1kHz, its impedance reduces to some 1600Ω and esr to some 0.25Ω, which is a slightly easier measurement task.

Similarly a 100 pF capacitor's impedance makes measurement at 1kHz extremely difficult. Increasing frequency to 1MHz produces an impedance of around 1600Ω and esr of near 1Ω for COG ceramic or polystyrene film.

Test lead or test jig inductance reduces the measured impedance value, so artificially inflates the measure capacitance. More importantly – especially for low loss capacitors – any test lead or jig resistance increases the measured esr value. This results in inflated loss factor measurements.

Both effects can be minimised by using the shortest possible test leads and the most appropriate method to connect the test capacitor to the measurement instrument. By way of example, two-terminal measurement of a 1nF capacitor at 1MHz via a total lead inductance of 1µH overstates the true capacitance by 4%, Fig. 1.

Conventional two-terminal measurements are acceptable when measuring capacitive impedances of more than 1kΩ. This equates to capacitance values less than 1.5µF at 100Hz,

Capacitor test instruments

This short listing, using only examples from Hewlett Packard[6], illustrates typical measurement equipment commercially available. Other manufacturers also offer measuring systems.

Hewlett Packard makes a range of *LCR* meters to suit most requirements and budgets. The *HP4263B* is a well established meter able to measure from 100Hz to 100kHz in five frequency steps and from 1pF to 1F or 10nH to 100kH, with a 0.1% basic accuracy. Complete with a component test jig, this meter costs around £3000.

The *HP4278* meter has the speed and precision needed for production capacitor testing. Providing the two most common test frequencies, 1kHz and 1MHz, this meter can test capacitors up to 200µF. Its basic accuracy is 0.05% at 1MHz and its measurement time is 21ms maximum.

Should you need a wider frequency range, the *HP4284* meter has similar basic accuracy, a maximum measurement time of 830ms at 1kHz and a choice of 8 600 test frequencies selectable from 20Hz to 1MHz. Capacitances from 0.01fF to 9.999F can be measured. This engineers tool, complete with a component test jig, costs around £8000.

Its companion meter, the *HP4285*, has a 0.1% basic accuracy and a wide test frequency range from 75kHz to 30MHz in 100Hz steps. It measures capacitors from 0.01fF to 999.99µF with a maximum measurement time of 200ms. Both meters also measure inductance.

The *HP4291* introduced the voltage/current impedance measurement method to frequencies from 1MHz to 1.8GHz. Having a basic accuracy of 0.8% it can measure a wide range of impedances.

The more recent *HP4286*, a dedicated *LCR* meter, offers similar performance measurements over a frequency range from 1MHz to 1GHz with a basic 1% accuracy.

150nF at 1kHz or 150pF at 1MHz. Larger capacitances or lesser impedances require use of four-terminal measurement leads or test jigs, as detailed in the panel entitled Four-terminal measurements.

The large magnitude differences between a capacitor's impedance or reactance and esr vectors means that accurate measurement of esr is much more difficult than is measurement of capacitance.

Since the capacitance value is much more easily measured than is loss factor, many low-cost instruments measure capacitance only. However while the capacitance value is important for circuit design calculations, it is esr which determines the power dissipated by the capacitor in use. The power dissipated results in heat, which ultimately determines the capacitors service life.

A quick measurement of capacitance can be helpful. But the esr figure is needed to allow the designer to discriminate between different capacitor makes and constructions. It allows you to ascertain a capacitor's suitability in power and pulse applications or even to confirm that an electrolytic capacitor has dried or worn out.

As you can see from the above numbers, a capacitor's esr is strongly frequency dependent. It may also be influenced by ambient temperature, ac test voltage and any dc bias voltage.

With most dielectric systems, the measured capacitance value is similarly affected by frequency, ambient temperature, ac test voltage and any applied dc bias voltage. Consequently, while these standardised test frequencies and voltages will be used in the maker's end-of-line production tests, measurements at other combinations are needed to quantify a capacitor's behaviour in the field.

Measuring esr

I said that esr is more difficult to measure than capacitance, but why? For an ideal capacitor, voltage and current have a phase difference of 90°. A practical capacitor exhibits resistive losses and a level of self inductance, resulting in a reduction of this phase angle.

A low-loss capacitor, such as the 0.1µF foil and polypropylene example above, would have a phase angle of 89.991° at 1kHz. The 100pF example's phase is 89.964° at 1MHz. Even the 10 000µF electrolytic example has a phase angle of 85.806° at 100Hz.

The small phase angle change between these first two examples – only 0.027° – quadruples the measured esr from 0.25 to 1.0Ω. This demonstrates how difficult it is to measure the esr of low-loss capacitors. It also emphasises the importance of minimising test lead or jig error contributions and optimising both accuracy and resolution of the phase angle measurement.

Measurement methods. Capacitance and esr can be measured by comparison with a known capacitor in a bridge circuit. Alternatively, capacitor current and phase angle can be measured while the device is stimulated by a known voltage.

One variation of this bridge circuit – the reflection bridge – measures the bridge's unbalance voltage and phase angle resulting from the test capacitor.[2]

The conventional ac Wheatstone capacitor bridge circuit has two precision variable resistance arms and a known standard capacitor. It suffers from a major disadvantage in that adjustment of one resistance arm affects the balancing conditions for the other arm. In practice, many interacting adjustments are required to attain the final loss factor balance, **Fig. 3.**

When measuring low-loss capacitors, this interaction is time consuming but acceptable. As capacitor loss increases – and especially with large value electrolytics – final balance may be impossible.[2]

The transformer ratio-arm bridge was developed many years ago to eliminate this problem. It results in almost complete independence when balancing capacitive and loss factor controls. It gave excellent results for capacitors to 10µF.

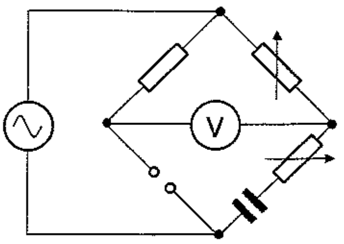

Fig. 3. The two balancing arms of this traditional ac Wheatstone capacitance bridge interact, needing repetitive adjustments. Measuring lossy capacitors, it is slow to balance.

A special low impedance adaptor was developed to measure impedances less than 10Ω. While this adaptor extended measurements to larger capacitance values, these cannot be read directly from the dials and accuracy is degraded.

Variations on Wheatstone

To overcome these balance interaction problems, many variations of the basic Wheatstone bridge were developed. One particularly useful exploration of balancing problems investigated ten different bridge configurations. Estimates of time to balance were derived for each configuration when measuring low or high loss components.[3]

Perhaps the most successful of these variants replaced one resistive balancing arm with a variable capacitance arm. When built many years ago to measure large value electrolytic capacitors, it proved to have almost complete independence between the capacitive and loss controls and provided a direct readout of esr. There's more on this in the panel entitled Capacitor bridge.

Recently, I needed to perform a series of difficult esr measurements at audio frequencies on capacitors having typically a 100V dc bias. No other suitable bridge being available, I built an up dated version. By including additional range switching this bridge could also measure smaller capacitance values and inductance, **Photo 1.**

I said earlier that these measurements could also be performed by measuring capacitor current and phase angle. For this measurement a resistor is used as a zero-phase reference standard. Accuracy of capacitance value measured depends on the sine of the measured phase angle, so may be little affected by measurement parasitics.

But esr depends on the cosine of the phase angle measured between the voltages on the capacitor and this standard resistor, so parasitics become important. Even at low frequencies, provision of a practical resistance standard free from capacitance and self inductance can prove difficult. **Fig. 4.**

Perhaps the best solution for practical experiments is to use a precision SMA 50Ω load or termination with a suitably accurate phase meter.[4] See also the panel entitled Impedance *V/I* measurements.

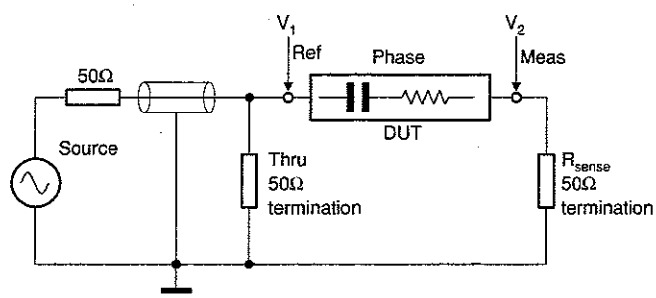

Fig. 4. Basic V/I impedance magnitude and phase angle measurement circuit, as used in LCR meters, is equally suited to measurements using lower cost discrete instruments.

Commercial *LCR* meters based on this approach and measuring to 1MHz have been available for more than a decade. One example can even measure at 30MHz, but commands a premium price. ■

What's next?
Having covered conventional capacitor measurement methods here, Cyril looks at reflection techniques in part 2. He also explores dielectric absorption, with results taken using a simple and easily repeated measurement method.

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Impedance V/I measurements

Impedance measurements can be performed using either a constant current or constant voltage source. Most engineers have a signal generator available so constant voltage tends to be the most popular.

Many writers advocate using a large value series resistor to approximate a constant current source. But when used to measure reactive loads – whether capacitors or inductors – this technique results in gross errors due to phase angle differences. This is easily confirmed in practice by measuring a known capacitor at low frequencies.

My preferred method, which I used to illustrate this series of articles, closely mimics the commercial *LCR* meter measurement methods, but uses available instruments. It was described in my article

Four-terminal measurements

A conventional two-terminal measurement of impedance uses the same test leads to pass the measurement current and measure the voltage drop at the device under test. This results in the measured voltage drop being overstated, according to the voltage drop along the test leads used and any contact resistances present.[2]

Using one pair of test leads to supply the test current and a second pair to measure the voltage drop at the device under test, while taking care to avoid mutually induced lead voltages, largely overcomes these errors, **Figs 5, 6**.

Using four coaxial test leads to replace the two pairs of leads, with Kelvin test contacts, eliminates almost all test lead errors.[2] The screens of the cables carry the return currents.

Occasionally a 'guard' or three-terminal technique is used to isolate the device under test from other circuit parasitics. Upgraded to the four terminal concept, this effectively becomes an accurate six terminal measurement.

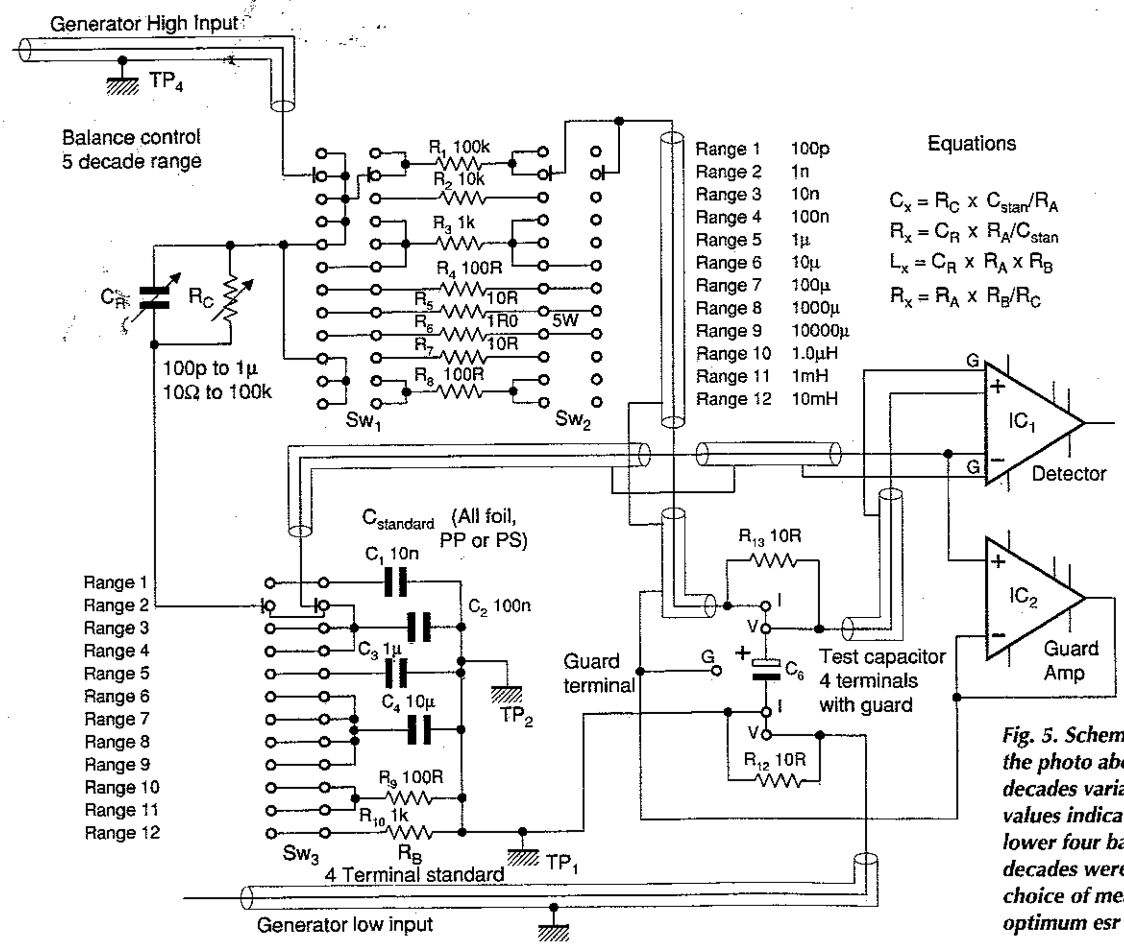

Fig. 5. Schematic of the bridge in the photo above. As built using five decades variable arms, the range values indicated need only use the lower four balancing decades. Five decades were built to provide a choice of measurement range for optimum esr balance sensitivity.