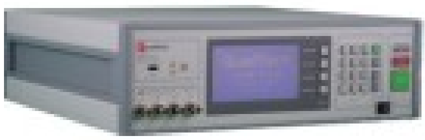
♦ PRECISION INSTRUMENTS FOR TEST AND MEASUREMENT ♦



LCR Measurement Primer

1st Edition, Feburary 2018

www.ietlabs.com

Contents

1 What is Impedance? 6
Phase Shift 6
Series vs. Parallel Equivalencies 7
2 History of Impedance Measurement 11
A Bridge to the Future Capacitance Measurements through the Ages 11
Analog Bridges 11
The Transformer & Printed Circuit Boards 12
3 Basic Measurement Techniques 15
4 Note: 1- terminal = 1 wire = 1 lead = 1 connection 21
Two-Terminal Measurements 21
Four-Terminal Measurements 21
Three-Terminal (or Guarded) Measurements 23
5 Measurements of Impedance 25
Functions 26
Test Voltage 26
Ranging 26
Integration Time 27
Median Mode 27
Computer Interface 27
6 Compensating for Impedance in Fixtures and Cables 28
Stray Capacitance 28
Open/Short Correction 29
Load Correction 29
7 Measurements of Capacitance 31
Series or Parallel 33
Measuring Large and Small Values of Capacitance 35
8 Measurements of Inductance 37
Series or Parallel 38
Inductance Measurement Factors 38
DC Bias Current 38
Constant Voltage (Voltage leveling) 39
Constant Source Impedance 39
DC Resistance and Loss 39
Loss: Copper, Eddy Current, and Hysteretic 39
9 Measurements of Resistance 41
Series or Parallel 41
10 Measurements of Impedance 42
Accuracy 43

Basic Accuracy 43
Actual Accuracy 44
Factors Affecting the Accuracy of Measurements 44
Example: Accuracy Formula for 7600 Plus Precision LCR Meter 45
1.0 for 0.100V < Vs ≤ 1.000V 45
Example Accuracy Graph 46
11 Dielectric Constant Measurement of Solids and Liquids 48
Measurement Methods, Solids: The Contacting Electrode Method 48
Air-Gap Method 49
Two-Fluid Method 50
Measurement Methods, Liquids 52
12 What an LCR Meter Should Do 53
Test Frequency 53
Test Voltage 53
Accuracy/Speed 53
Measurement Parameters 53
Ranging 53
Averaging 53
Median Mode 54
Computer Interface 54
Display 54
Binning 55
Nested Limits 55
Sequential Limits 55
Test Sequencing 56
Parameter Sweep 56
Bias Voltage and Bias Current 57
Constant Source Impedance 57
Monitoring DUT Voltage & Current 58
13 Examples of Precision LCR Meters 59
DE 5000 Handheld LCR Meter 59
1659 Digibridge RLC Meter 59
1692 Digibridge RLC Meter 59
1900 Series Precision LCR Meters 60
1689 Digibridge RLC Meter 60
1693 Digibridge RLC Meter 61
7600 Plus Precision LCR Meter 61
Dedicated Function Test Instruments 61
14 Impedance Terms and Equations* 62
15 NRTLs and Standards Organizations 64
16 Helpful Links 65
17 Typical Measurement Parameters 67
18 LCR Selection Guide 69

19	70	
20	LCR Accessory Selection Guide	71
21	IET Labs Application Notes	72
22	Glossary	72

Preface

This primer explains the measurement of the impedance parameters known as L (inductance), C (capacitance), and R (resistance). Impedance parameters are characteristic of an AC circuit; this primer describes the impedance measurements that are typically used, including their equations. Also described are the connections to the device under test, and how to use test instruments to precisely measure impedance. In addition, primer describes the testing of individual passive components for inductance, capacitance, and resistance.

1 What is Impedance?

Electrical **Impedance (Z)**, is the total opposition that a circuit presents to alternating current. Impedance changes according to the components in the circuit and the frequency of the applied AC. Impedance can include **resistance (R)**, **inductive reactance (X_L)**, and **capacitive reactance (X_C)**. It is not simply the algebraic sum of the resistance, inductive reactance, and capacitive reactance. Inductive reactance and capacitive reactance are 90^o out of phase with the resistance, so that their maximum values occur at different times. Therefore, vector addition must be used to calculate impedance.

In a circuit supplied by DC, resistance is the ratio of applied voltage (V) to resulting current (I). This is Ohm's Law.

$$\text{For DC, Resistance, } R = \frac{V}{I}$$

An alternating current regularly reverses its polarity. When an AC circuit contains only resistance, the circuit resistance is determined by Ohm's Law, too.

However, when capacitance and/or inductance are present in an AC circuit, they cause the voltage and current to be out of phase. Therefore, Ohm's law must be modified by substituting impedance (Z) for resistance. Ohm's Law becomes: Z = V/I, where Z is a complex number.

$$\text{For AC, Impedance, } Z = \frac{V}{I} = R + jX$$

Z is a complex number; i.e., it has a real component (R) and an imaginary component (jX). The imaginary component represents any point on the AC waveform.

Phase Shift

The resistance is always in-phase with the voltage. Therefore a phase shift is always relative to the resistance line. When the circuit has more resistance relative to inductive reactance, the impedance line moves toward the resistance line (X axis) and the phase shift decreases. When the circuit produces more inductive reactance relative to resistance, the impedance line shifts toward the inductive reactance line (Y axis) and the phase shift increases.

The impedance in a circuit with resistance and inductive reactance can be calculated using the following equation. If capacitive reactance was present in the circuit, its value would be added to the inductance term before squaring.

$$Z = \sqrt{\left(X_L^2 + R^2\right)}$$

The **phase angle** of the circuit can be calculated using the equation below. If capacitive reactance was present in the circuit, its value would be subtracted from the inductive reactance term.

$$Tan\phi = \frac{X_L}{R}$$

A phase shift can be drawn in a vector diagram showing a series impedance, Z, its real part Rs (series resistance), its imaginary part jXs (series reactance), and the phase angle θ.

$\omega = 2\pi f$

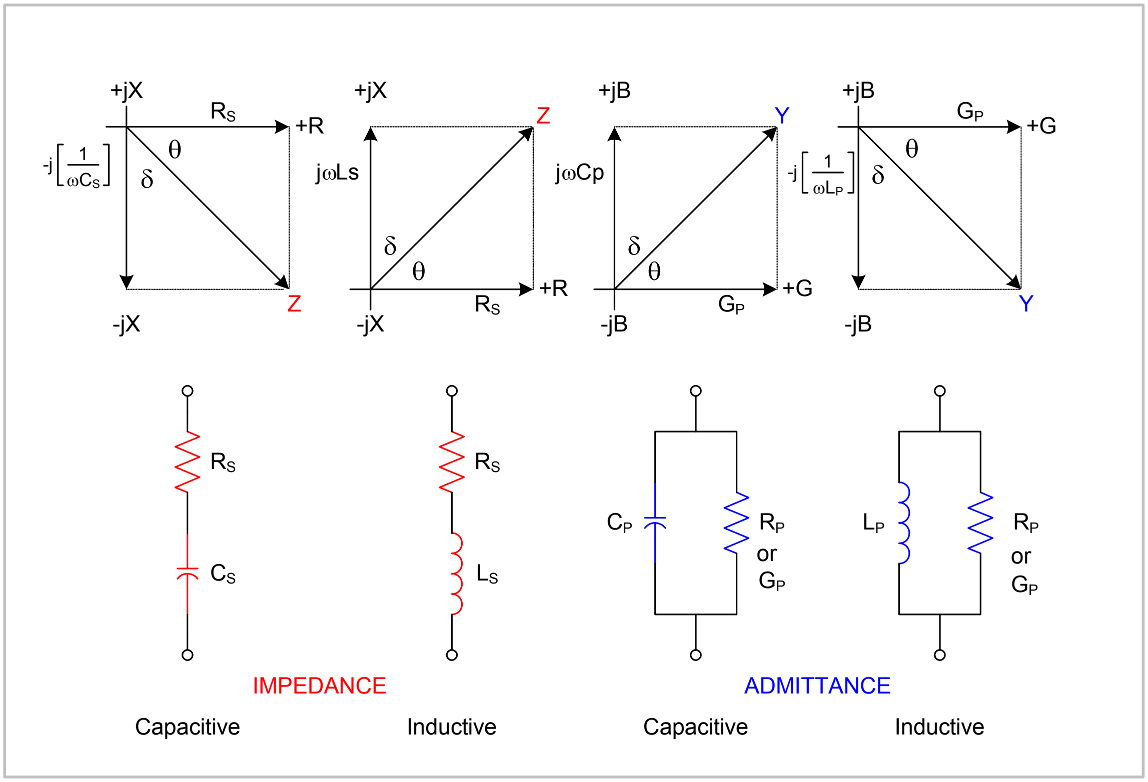


Figure 1. A Set of Vector Diagrams

When there is either inductance or capacitance in a circuit, voltage and current are out of phase.

Inductance	Voltage across the inductor is maximum when the rate of change of the current is greatest. For an AC (sinusoidal) wave form, this is at the point where the actual current is zero. The voltage applied to an inductor reaches its maximum value a quarter-cycle before the current does, and the voltage is said to lead the current by 90^{o}.
Capacitance	Current flowing through the capacitor is directly proportional to the value of the capacitor itself (high value capacitors charge more slowly), and is directly proportional to the change in capacitor voltage over time. Current applied to a capacitor reaches its maximum value a quarter-cycle before the voltage; current leads the voltage by 90^{o}.across the capacitor.

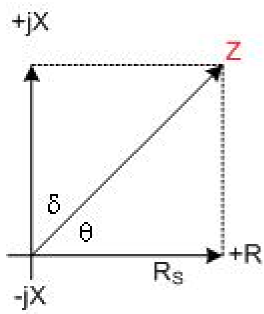
Series vs. Parallel Equivalencies

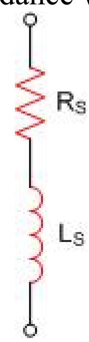
Which should be measured, series or parallel parameters? It depends on the purpose of the measurement. For incoming inspection and production measurements on passive components usually the series values is specified in EIA and MIL standards. These standards also specify test frequencies and other test conditions.

To determine the DC value of a **resistor** using AC measurements, use series measurements of low-valued resistors (say under 1k); use parallel measurements of high-valued ones. In most cases, this avoids errors due to series inductance and parallel lumped capacitance. Also, use a low test frequency. Note that sometimes an AC measurement can give the correct DC value better than a DC measurement because thermal voltage and drift errors are avoided and measurement sensitivity is apt to be higher.

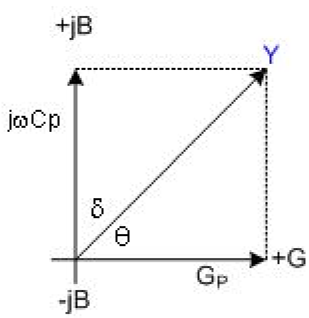
Other cases where parallel measurements are preferred are when measuring very low values of capacitance, when making measurements on dielectric and magnetic materials, and, of course, when trying to determine the separate values of two components in parallel. Very often the D of a capacitor is less than .01 so that it doesn't make any difference which is measured because the difference between the series and parallel values is less than .01%. Likewise, the Q of a resistor is usually less than .01 so that either resistance quantity can be measured.

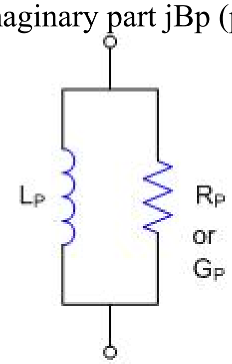
An equivalent circuit for this impedance would put Rs and Xs in series, hence subscript ‘s’.





The reciprocal of Z is Admittance (Y), which is also a complex number having a real part Gp (parallel conductance) and an imaginary part jBp (parallel susceptance) with a phase angle φ.





For a complete list of Impedance Terms & Equations, please see Page 62.

Resistance, R, can be specified by a single real number and the unit is the Ohm (Ω). The conductance, G, of a device is the reciprocal of its resistance: $G = 1/R$. The unit of conductance is the Siemen (formerly mho, 'Ohm' spelled backwards).

For AC, the ratio of voltage to current is a complex number because AC voltages and currents have phase as well as magnitude. This complex number is called impedance, Z, and is the sum of a real number, R, and an imaginary one, jX, (where j = -1). Thus, $Z = R + jX$. The real part is the AC resistance and the imaginary part is the reactance. Both have units of Ohms.

Reactance comes in two types, inductive and capacitive. The reactance of an inductive element is L, where L is its inductance and = 2πf (where f = frequency). The reactance of a capacitive element is negative, -1/ C, where C is its capacitance. The negative sign occurs because the impedance of a pure capacitor is 1/j C and 1/j = -j.
Because the impedance of two devices in series is the sum of their separate impedances, consider an impedance as the series combination of an ideal resistor and an ideal capacitor or inductor. This is the series equivalent circuit of an impedance comprising an equivalent series resistance and an equivalent series capacitance or inductance. Using the subscript s for series, we have:

$$1: \quad Z = Rs + jXs \quad = Rs + j\omega L \quad = Rs - \frac{j}{\omega C}$$

For a network having many components, the element values of the equivalent circuit change with the frequency. This is also true of the values of both the inductive and the capacitive elements of the equivalent circuit of a single, actual component (although the changes are usually very small).
Impedance is represented, at any specific frequency, by an equivalent circuit. The values of these elements or parameters depend on which representation is used, series or parallel, except when the impedance is purely resistive or purely reactive. In such cases only one element is necessary and the series or parallel values are the same.
Admittance, Y, is the reciprocal of impedance as shown in equation 2:

$$2: \quad Y = \frac{1}{Z}$$

It, too, is a complex number, having a real part, the AC conductance G, and an imaginary part, the susceptance B. Because the admittances of parallel elements are added, Y can be represented by a parallel combination of an ideal conductance and a susceptance, where the latter is either an ideal capacitance or an ideal inductance. Using the subscript p for parallel elements, we have equation 3:

$$3: \quad Y = Gp + jBp \quad = Gp + j\omega Cp \quad = Gp - \frac{j}{\omega L}$$

In general, Gp is not equal to 1/Rs and Bp is not equal to 1/Xs (or -1/Xs) as one can see from the calculation in equation 4.

$$4: \quad Y = \frac{1}{Z} = \frac{1}{Rs + jXs}$$

$$= \left[\frac{Rs}{Rs^2 + Xs^2} - \left(j\frac{Xs}{Rs^2 + Xs^2} \right) \right]$$

$$= \quad Gp + jBp$$

Thus Gp = 1/Rs only if Xs = 0, which is the case only if the impedance is a pure resistance; and Bp = -1/Xs (note the minus sign) only if Rs = 0, that is, the impedance is a pure capacitance or inductance.

Two other quantities, D and Q, are measures of the "purity" of a component, that is, how close it is to being ideal or containing only resistance or reactance. D, the dissipation factor, is the ratio of the real part of impedance, or admittance, to the imaginary part. Q, the quality factor, is the reciprocal of this ratio as illustrated in equation 5.

$$5: \quad D = \frac{Rs}{Xs} = \frac{Gp}{Bp} = \frac{1}{Q}$$

2 History of Impedance Measurement

A Bridge to the Future Capacitance Measurements through the Ages

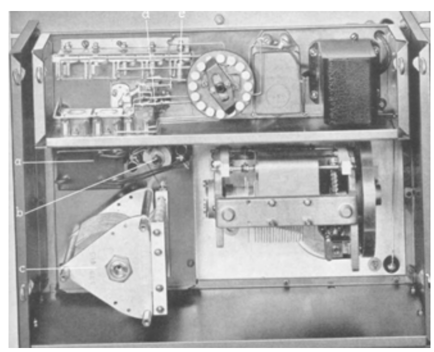
How did we get to the highly accurate LCR instrumentation we have today? Where did we get the technology for increased speed and precise accuracy over such a wide range of frequencies?

Melville Eastham formed General Radio Company in 1915. Let's take a look at General Radio's instrumentation line from conception to present day. Just how did we get from the large analog instruments with adjustable steel knobs and dials to the sleek digitally controlled units we now have that require only the push of one button?

Analog Bridges

Bridges were big back in the 1920s, the electrical kind that is as shown at right. In 1921 General Radio introduced the 216 Capacity Bridge, the first of it's kind. Capacitance from 1uuF to 10uF could be measured at a frequency of 200 - 10,000cps. The term cps (cycles per second) was used as the unit of frequency until the late 1960's when the unit Hertz (Hz) was adopted. This ratio-arm bridge was not a stand-alone unit however and needed an external power source, null indicator, capacitance standard(s) and balancing condenser for operation. Still this instrument gave precise readings for small values of capacitance with an accuracy of approximately 0.1%.

The word capacity, coined by Faraday, was used to describe the charge potential between two plates until the 1930's when the term capacitance superseded it. In the 1930's measuring instrumentation was developing rapidly using vacuum tubes and quartz crystals, trying to meet the demands of radio frequency measurements.



In 1939/40, Hewlett Packard produced the HP200 Oscillator from a General Radio patent where no inductors were used, just resistors and capacitors with degenerative feedback. This design feature substantially reduced cost. In 1945 General Radio released the GR 720A Heterodyne Frequency Meter that contained a butterfly circuit consisting of a variable air capacitor. Both circuit inductance and capacitance vary up or down simultaneously without the use of sliding contacts. When used in the rf oscillator circuit, this design permitted wide variations in frequency with a single turn of the control knob.

The bridge circuitry used in the 1942 Type 716-B capacitance bridge provided two measurement methods: direct or substitution. Using the Direct method, capacitance measurements of 100uuf (100pf) to 1uF and dissipation factor measurements of 0.002% to 56% (0.00002 – 0.56) were possible. Using the Substitution method, the capacitance range was 0.1pf to (1nf with internal standard) or to 1uf with external standards. The dissipation factor (ratio of component's real resistance to imaginary reactance) was calculated as 56%(C'/C_X) where C' is the capacitance of the standard condenser and C_X is the capacitance of the unknown. Along came the bipolar transistor in 1948 developed by Shockley, Bardeen and Brattain at Bell Telephone Laboratories. It still had to be proved, but transistors would turn out to consume less power, be less costly and more reliable than the vacuum tube.

The Transformer & Printed Circuit Boards

In the 1950's television was big as was jet aircraft. Measuring the fuel gauges in jet aircraft was complicated as jet fuel is a non-homogeneous chemical compound that exhibits a broad range in dielectric constant. With jet fuel, the expansion in volume during heating is balanced by the reduction in dielectric constant. The capacitance is a measure of the height of the fuel in the tank and a self-balancing bridge should indicate an accurate fuel level. A sensing element is added to the fuel tank to introduce the appropriate correction to the bridge circuit. General Radio developed the MD-1 Field Variable Capacitance Tester to adjust and calibrate this fuel gauge technology.

The 1960's brought great change in the electronics and instrumentation industry not to mention to society in general. Much research was being done in the field of semiconductors specifically for the space program that would revolutionize the industry a decade later but in the mean time transistors ruled the circuit world. Smaller circuit boards consisting of more reliable transistors were used in instrumentation. Dedicated 'plug-in' circuit boards provided easier access for calibration and repair reducing 'down time' for the instrument. In 1964, General Radio introduced the 1680-A Automatic Capacitance Bridge using a transformer ratio-arm bridge. Basic accuracy was ±0.1% over a capacitance range of 1pF to 1000uF at frequencies of 100cps, 400cps or 1000cps. We had adopted picofarad (pF) as 10^{-12} instead of uuF. Back to the 1680-A tester, dissipation factor was measurable from 0.0001 to 1.0 and 2 measurements per second were possible.

One precision capacitance meter that has stood the test of time as one of the great 0.01% bridges is the GenRad 1620 and 1621. These are true wheatstone bridges and have the capability of measuring capacitance and dissipation factor over a wide range with an accuracy of 0.01% at frequencies from 20 Hz - 20 kHz (or higher) with an 0.01% accuracy, 1-ppm resolution.

Silicon Revolution & Digital Signal Processing

A patent issued in January 1980 for the GenRad DigiBridge™ resulted in the manufacture of the highly accurate 1600 line of digital bridges that employed a synchronous detector circuit solving the automation difficulties of the former balanced bridge detector. Capacitance measurements from 0.00001pF to 99999uF with a basic accuracy of 0.02% over 500 programmable test frequencies (12Hz to 200kHz) were attainable. High-speed options were available increasing test speed to 30 measurements per second or 50 measurements per second depending on model. Two U.S. patents: #4196475: 'the method and apparatus for automatic measurement of impedance or other parameters with microprocessor calculation techniques' and #4342089: 'the method and apparatus for automatic measurement of circuit parameters with microprocessor calculation techniques' where the basis for most modern LCR Meters.

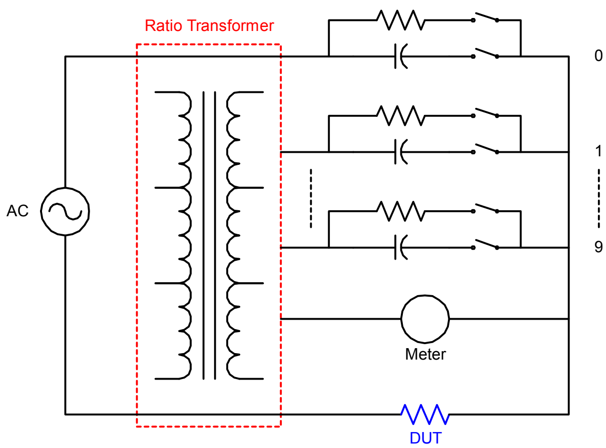
Digital signal processing (DSP) techniques were commonly employed in 1990's instrumentation design as IC cost decreased. Digital sine wave generation, digital sampling and synchronous detection increased not only the speed of the capacitance measurement but the measurable range of frequency as well. Accuracy of the IET Labs, now IET Labs (formerly GenRad Instrumentation Line), 7000 Series Precision LCR Meter was 0.05%, basic accuracy, over the range 10Hz to 2MHz at a speed of 1 measurement per second. To trade accuracy for speed one need only select FAST mode to make 40 measurements per second at an accuracy of 0.5%. Versatility in capacitance measurement instrumentation was key as the specific test application took precedence over design bells and whistles. Production line applications were interested in speed with a basic accuracy. Standards Laboratories and R&D Centers were more interested in highly precise measurements at very specific frequencies.

Instrumentation design engineers are designing to customer specification. Capacitance measurements are being made in Quality Control labs on the materials (such as tantalum powder) that comprise the finished product before assembly to ensure the dielectric meets the end-users rigid requirements. Production Lines need capacitance instrumentation to meet international and national testing standards. New equipment design, automation and reduction of cost have brought product manufacturers the best in LCR instrumentation. Today's new equipment provides the most essential passive component tests all in one convenient box. The ability to reconfigure the hardware and software of an instrument is especially useful in a production environment for making the box fit the test.

Programming and remote capabilities allow full device characterization with the push of one button.

3 Basic Measurement Techniques

Early commercial LCR "bridges" used a variety of techniques involving the matching or "nulling" of two signals derived from a single source. The first signal generated by applying the test signal to the unknown and the second signal generated by utilizing a combination of known-value R and C standards. The signals were summed through a detector (normally a panel meter with or without some level of amplification). When zero current was noted, it could be assumed that the current magnitude through the unknown was equal to that of the standard and that the phase was exactly the reverse (180° apart). The combination of standards selected could be arranged to read out C and D_F directly as in the IET Model 1620 and 1621 Capacitance Bridges. Automatic bridges have generally not used the nulling technique but rely on a combination of microprocessor control and phase sensitive detectors.

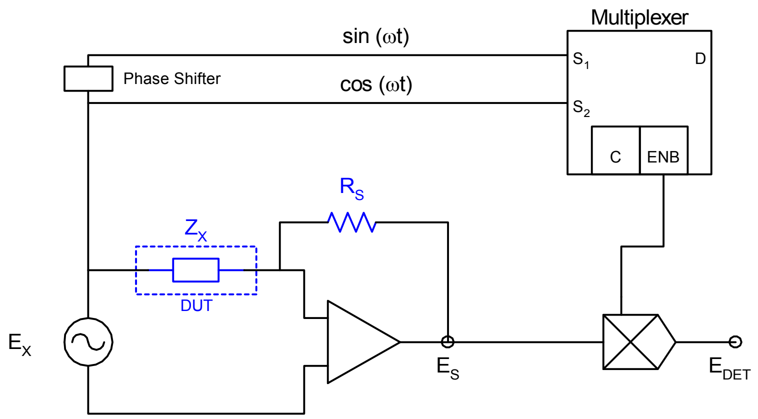


Ratio Transformer Method of Null Detection

The Phase Sensitive Detector

The balanced bridge detector is not well suited to automation due to the many sensitive nodes that must be switched to achieve a null. In the late 1970s H.P. Hall of GenRad Instruments introduced his design of a synchronous detector circuit to solve this problem. Mr. Hall's synchronous detector invention was granted U.S. Patent # 4,181,949.

Whereas the null detector uses a combination of precisely known standards, the synchronous detector utilizes a single (reference) resistor (R_S) of relatively low accuracy. The detector operates by gathering either the in-phase or quadrature component of the current through the unknown. This is accomplished by multiplying the current by the sine of the stimulus for the in-phase component or the cosine for the quadrature.



Basic Synchronous Detector Circuit

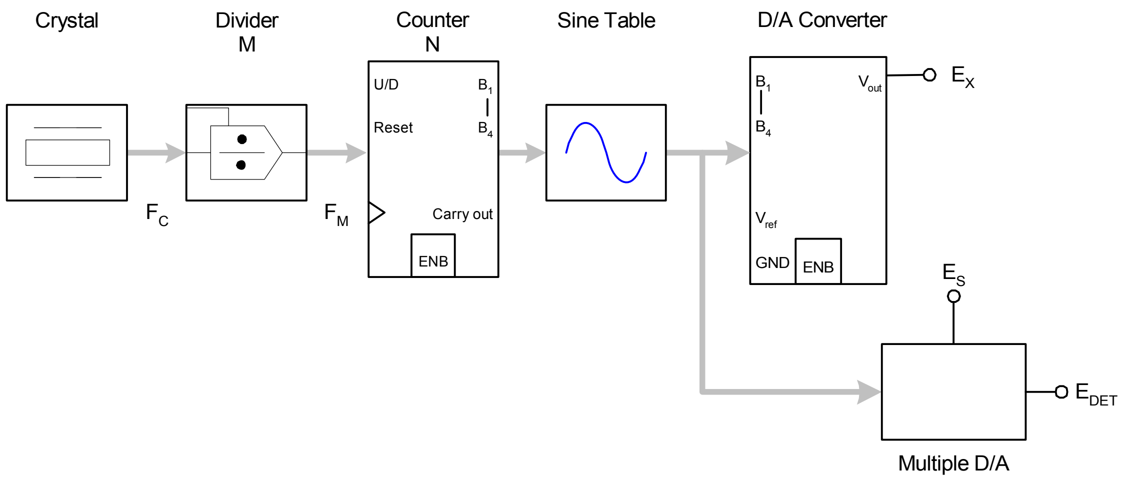
Depending upon which input to the multiplexer is selected, the detector voltage, E_{DET}, will represent E_S [sin (ωt)] or E_S [cos (ωt)]. Since the voltage applied is known, the admittance of the DUT, as a complex vector, can be calculated. $Z_X = R_S (E_X/E_S)$. From the admittance, any desired parameter may be calculated.

In order for the technique to be effective, the arithmetic requires that:

1. The current representation, Es, and the sine wave being multiplied are synchronous to the stimulation signal Ex. Any phase relationship between the signals is acceptable as long as it is constant throughout the detection time.

2. The multiplication is performed over an integer number of cycles.

The technique of choice for multiplying the two signals has been to use a multiplying D/A converter. The signal, Es, is applied to the reference input of the D/A and a series of binary numbers representing a sine or cosine wave are applied to the digital input. In order to achieve synchronization, the sine wave stimulus is generated by applying the identical binary stream to a second D/A converter.



Digital Sine Wave Generation and Synchronous Detection

The method of using the same binary stream to drive both D/A's simultaneously assures perfect synchronization. This implementation has worked well providing flexible, automatic measurement capability with a high degree of precision and speed. It has two factors that have limited its effectiveness: the bandwidth of the multiplying D/A, and the ability of the source to generate frequencies with a high degree of resolution. Multiplying four quadrant D/A's with bandwidth above a few hundred kilohertz is simply not available at reasonable cost.

The frequency generation scheme provides synchronization by using a ROM look-up table to drive both D/A's. A binary counter that repeatedly counts from 0 to N drives this ROM look-up table. N is the size of the look-up table and is typically in the range of 64-1024. The frequency of the sine wave is $F_C/(M \bullet N)$. The difficulty is that the division is integer, and not all frequencies can be produced.

For a sine table of size 256, and a crystal frequency of 38.6 MHz, the following may be produced:

M=1	f=150 kHz
M=2	f=75 kHz
M=3	f=50 kHz

As can be inferred from the above example, no combination of crystal frequency and N will produce all desired frequencies in a general-purpose meter. If one is willing to reduce the number of "sample points" from the look-up ROM (resulting in more noise) the value of N can be adjusted in concert with M to provide additional values. In practice there have always been a large number of desirable values of f that can only be approximated.

Direct Digital Synthesis

The Direct Digital Synthesis (DDS) approach has been used for some time to generate sine waves for test and measurement purposes. A variety of commonly available equipment, such as arbitrary waveform generators and modems utilize DDS in integrated circuit form to great advantage.

The DDS is a variation of the Sine ROM look-up that provides very high resolution of the generated frequency, Fg. Like the counter driven look-up, a DDS provides phase information to a Sine ROM table to drive a D/A. Whereas the counter provides the identical phase numbers over and over to the ROM (0-N), a DDS varies the phase points from cycle to cycle to provide a higher resolution. The counter always returns to phase "zero" at the beginning of each cycle, the DDS does not necessarily do so.

To create a specific frequency, the DDS is loaded with a phase increment, a digital word of high precision (typically 32 bits) that is a representation of the step size between ROM table look-ups. This phase increment is continuously added to a phase accumulator whose output is applied to the sine look-up table. The sine look-up table is normally of considerably less precision than the accumulator (say 16 bits). The look-up results are then truncated to 8, 10, or 12 bits and applied to a D/A for generation of the sine wave. The frequency (Fg) generated by a 32-bit accumulator running at 30MHz is:

$$Fg = \frac{Fs \times \Delta\Phi}{2^n} = \frac{30 \times 10^6 \times \Delta\Phi}{2^{32}}$$

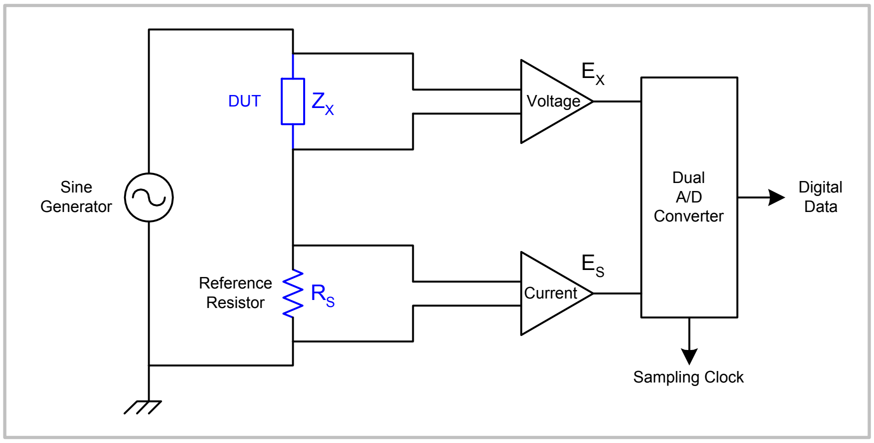
The phase increment is not necessarily an even multiple of 2π. This being the case, on completion of the first cycle the phase accumulator would not return to zero but would start the next cycle at some point beyond zero degrees. Typical commercially available IC's are capable of producing sine waves from 1Hz to 20MHz with .004Hz resolution. The resolution available with a 32-bit accumulator clocked at 30MHz is:

$$R = \frac{Fs}{2^{32}} = \frac{30 \times 10^6}{2^{32}} = 0.00698\,Hz$$

From these numbers we see that extremely fine resolution may be obtained.

Digital Sampling

In order to overcome the bandwidth limitations of multiplying D/A's, a number of investigations have been launched using digital sampling techniques to analyze the current signal through the unknown. A representative implementation is illustrated in Figure 4.



Digital Detector Circuit

The voltage across the standard (reference) resistor Rs is applied to an A/D converter that takes samples during one or more integer cycles of the stimulus sine wave. The number of samples, N, per sine wave is usually a power of 2 in the range 64 to 1024. The voltage across the unknown is also sampled at the same rate and time. When the samples from each of the two channels are collected, they are multiplied mathematically by the sine and cosine of the appropriate angle by a microprocessor. Due to speed considerations, it is common to utilize a DSP. This algorithm results in obtaining the real and imaginary parts of the two voltages. The admittance of the unknown can then be calculated. $Z_X = R_S (E_X/E_S)$.

While the digital technique eliminates the multiplying D/A, it replaces it with an A/D converter that must be able to sample the waveform at N times the sine wave frequency. For N=64 and a test frequency of 1MHz, this requires a sampling A/D with a rate of 64MHz! Fortunately this requirement may be overcome by using a technique known as under sampling.
In under sampling, the A/D converter still takes the same number of samples of the signal, but it does so over multiple cycles.

For example: four samples are needed from a test signal of 1MHz (1µsec period), and the A/D can only sample at 100kHz (10µsec period). The first sample is taken at the beginning of the first cycle (0°) then the second is not taken until ten cycles have passed (10 • 1µsec = 10µsec). At this point the wave would be sampled at 90° and the third sample 10 cycles later at 180°. The last 10 cycles after that at 270°. Thus a total of 30 cycles of the stimulus is required to fetch all the data.

Today

IET Labs has utilized the described methods of digital sampling and DDS generation of the sine wave in the 7600 Plus Precision LCR Meter. The DDS pair employed in the 7600 Plus LCR Meter generates sine waves from 10Hz to 2MHz. The resolution available is 0.1Hz from 10Hz to 10kHz, and five digits of resolution above 10kHz. The circuit design was done quite conservatively and there is every reason to believe that this resolution may be increased in the future.

The sampling circuit of the 7600 Plus instrument utilizes two fast ‘sample-and-hold’ IC's in front of a dual 18-bit Analog to Digital converter. The sampling rate is a maximum of 80kHz. The under-sampling technique is working well up through the range of frequencies. The

combination of DDS and sampling detector is providing 0.05% accuracy on primary parameters (R, L, C) and 500ppm on secondary parameters such as D_F and Q. The units were designed as bench top analyzers with speed as a secondary consideration, but in FAST mode will measure at 40 measurements per second.

4 Note: 1- terminal = 1 wire = 1 lead = 1 connection

Two-Terminal Measurements

When the DUT is very small and you have no test fixture to accommodate four terminals, this may be your only option. With only two terminals, however, the same terminals must be used for both applying a current and measuring a voltage.

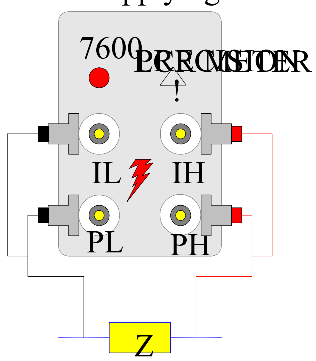


Figure 2. Two-Terminal Measurement

When a device is measured in this way, there are two types of errors—and these are the errors that measurements with more connections will avoid; one error is the lead inductance and lead resistance in series with the device and the other is stray capacitance between the two leads. Because of these error sources, the typical impedance measurement range for a two-terminal connection is limited to 100Ω to 10kΩ.
The use of multiple connections can reduce or remove impedance measurement errors caused by series impedance in the connections or shunt impedance across the unknown.

Four-Terminal Measurements

First let's jump into four-terminal measurements, which are simpler to explain and more commonly used than a three-terminal measurement. With a second pair of terminals available, one can measure voltage across the device with one pair and apply current to the device with the other pair. This simple improvement of independent leads for voltage and current effectively removes the series inductance and resistance error factor (including contact resistance) and the stray capacitance factor discussed with two-terminal measurements. Accuracy for the lower impedance measurement range is now substantially improved down to 1Ω and below. There will be some mutual inductance between the current leads and voltmeter leads which will introduce some error, but much of this is eliminated by using shielded coaxial cabling. The most famous use of the four-terminal connection is the Kelvin Bridge, which has been widely used for precision DC resistance measurements.

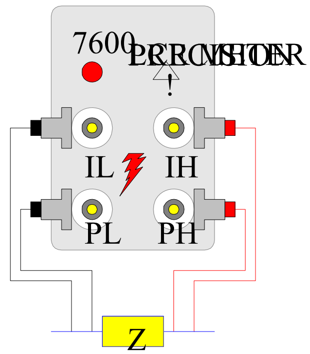


Figure 3. Four-Terminal Measurement

Kelvin's name is synonymous with the four-terminal connection technique. "Kelvin clips" are the tools that commonly make this connection.

Three-Terminal (or Guarded) Measurements

While the four-terminal measurement applies a current and measures the resulting open-circuit voltage, the three -terminal measurement does the opposite: it applies a voltage and measures the short circuit current. The extra terminal, or third terminal, is called the guard. Any components shunting the unknown can effectively be removed by connecting some point along the shunt to this guard terminal.

The effect of any stray path, capacitive or conductive, (shunting Zx) can be removed by intercepting it with a shield tied to the guard point. Likewise, "shunting Zx" can effectively be removed in a series string of actual components by connecting some point along the string to the guard and making a three-terminal measurement. Sometimes three-terminal measurements are simply called guarded measurements. They are also called direct impedance measurements.

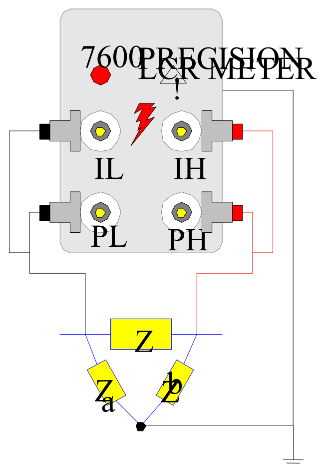


Figure 4. Three-Terminal Kelvin

The impedance Zx is directly between points A and B. As shown by equation 6, errors caused by Za and Zb have been changed. If it were not for the series impedances, the effect of Za and Zb would have been removed completely. The combination of series impedance and shunt impedance has given us two new types of errors. We'll call the first (z1/Za and z3/Zb) the "series/shunt" error. It's caused by a voltage divider or a current divider. The voltage between point A and guard is reduced because the attenuating or dividing effect of the impedances z1 and Za. Likewise, Zb and z3 divide the current Ix so that it doesn't all flow in the ammeter. This error is a constant percentage, independent of the value of Zx. It usually is very small at low frequencies unless the series and shunt impedances are actual circuit components as they might be in in-circuit measurements.

A three-terminal connection usually employs two coaxial cables, where the outer shields are connected to the guard terminal of the LCR meter. The guard terminal is electrically different from the instrument ground terminal, which is connected to chassis ground. Measurement accuracy is usually improved for higher impedances, but not lower because lead inductance and resistance are still present.

Equation 6:

$$Z_m = \frac{V}{I}$$

$$= Z_x\left(1 + \frac{z_1 + z_3}{Z_x} + \frac{z_1}{Z_a} + \frac{z_3}{Z_b} - \frac{z_5 Z_x}{Z_a Z_b}\right)$$

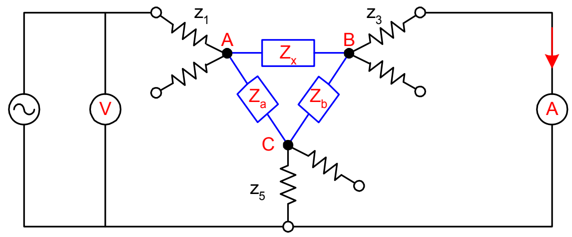


Figure 5. Three-Terminal Guarded using Delta Impedance Configuration

5 Measurements of Impedance

Digital LCR meters measure the current (I) flowing through a device under test (DUT), the voltage (V) across the DUT, and the phase angle between the measured V and I. From these three measurements, all impedance parameters can then be calculated. A typical LCR meter has four terminals labeled IH, IL, PH and PL. The IH/IL pair is for the generator and current measurement and the PH/PL pair is for the voltage measurement.

There are many different methods and techniques for measuring impedance. The most familiar is the nulling type bridge method. When no current flows through the detector (D), the value of the unknown impedance Zx can be obtained by the relationship of the other bridge elements, shown in equation 7.

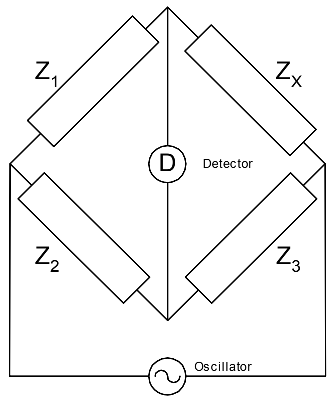


Figure 6. Nulling Bridge

$$7: \quad Z_x = \frac{Z_1}{Z_2} Z_3$$

Various types of bridge circuits, employing combinations of L, C, and R as bridge elements, are used in different instruments for varying applications.

Most recently instruments have been developed which employ elaborate software-driven control and signal processing techniques. For example, the IET Labs 7600 LCR Meter uses a principle of measurement which differs significantly from that employed by the traditional measuring instruments. In particular, the 7600 uses digital techniques for signal generation and detection. Both the voltage across the device under test (Zx) and the voltage across a reference resistor (Rs) are measured, which essentially carry the same current.

The voltage across Zx is Vx and the voltage across Rs is Vs. Both voltages are simultaneously sampled many times per cycle of the applied sine wave excitation. In the case of the 7600, there are four reference resistors. The one used for a particular measurement is the optimal resistor for the device under test, frequency, and amplitude of the applied AC signal. For both Vx and Vs a real and imaginary (in phase and quadrature) component are computed mathematically from the individual sample measurements.

The real and imaginary components of Vx and Vs are by themselves meaningless. Differences in the voltage and current detection and measurement process are corrected via software using calibration data. The real and imaginary components of Vx (Vxr and Vxi) are combined with the real and imaginary components of Vs (Vsr and Vsi) and the known characteristics of the reference resistor to determine the apparent impedance of the complex impedance of Zx using complex arithmetic.

Functions

The demand on component testing is much more than a resistance, capacitance or inductance value at a given test frequency and stimulus voltage. Impedance meters must go beyond this with the flexibility to provide multi-parameters over wide frequency and voltage ranges. Additionally, an easily understood display of test results and the ability to access and use these results has become increasingly important.

Test Voltage

The AC output of most LCR meters can be programmed to output the signal level to the DUT. Generally, the programmed level is obtained under an open circuit condition.
A source resistance (Rs, internal to the meter) is effectively connected in series with the AC output and there is a voltage drop across this resistor.   When a test device is connected, the voltage applied to the device depends on the value of the source resistor (Rs) and the impedance value of the device.
Here are the factors of constant source impedance, where the programmed voltage is 1V but the voltage to the test device is 0.5V.

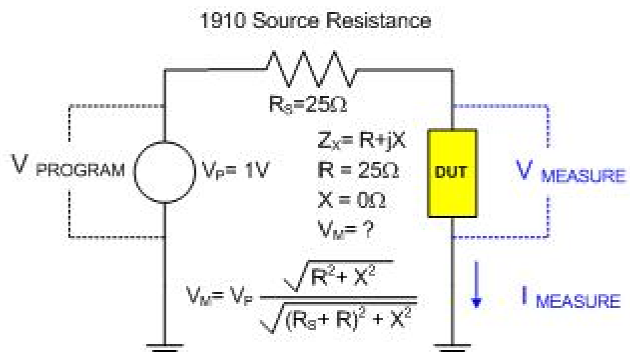


Figure 7, Source Impedance Factors

LCR meters have a voltage leveling function, where the voltage to the device is monitored and maintained at the programmed level.

Ranging

In order to measure both low and high impedance values, the instrument must have several measurement ranges. Ranging is usually done automatically and selected depending on the impedance of the test device. Switching range resistors and the gain of detector circuits maintain the maximum signal level and the highest signal-to-noise ratio keep the measured impedance close to full scale for any given range.
Range holding, rather than auto ranging, is a feature sometimes used in specific applications. For example, when testing components of similar value, range holding reduces test time. Range holding is also effective when measuring components whose value falls within the

overlap area of two adjacent ranges. In this case, auto range causes the instrument's display to change, possibly confusing the operator.

Integration Time

When integration of analog signals occurs over more cycles of the test, the measurement time will be longer but more accurate. Measurement time is controlled by the operator, who selects a FAST or SLOW mode.
To improve repeatability (precision), try the Averaging mode, in which multiple measurements are made and the average of these calculated. This is a way of reducing noise, but does take time.

Median Mode

A further gain in precision is by means of the Median mode. Three measurements are made and the lowest and the highest are discarded. The remaining value then represents the measured value for that particular test. Median mode will increase test time by a factor of 3.

Computer Interface

Today's testers need a standard data communication interface to a host computer data processing or remote control. For an operation retrieving only pass/fail results, Programmable Logic Control (PLC) is often adequate, but for data logging it's a different story. The typical interface for this is the GPIB general purpose interface bus, USB universal serial bus or the RS-232 serial communication line.
These interfaces are necessary for process control in component manufacturing as well as in data archiving. For example, when testing 10% of components, the yield is fine when components test at 8% or 9%, but it does not take much of a shift for the yield to plummet. The whole idea of production monitoring is to reduce yield risks and correct the process quickly if needed. An LCR Meter with remote interface is standard in many test applications where data logging or remote control are common.

6 Compensating for Impedance in Fixtures and Cables

Compensating for the residual capacitance and residual impedance of test fixtures and cables is an important phase in ensuring the accuracy of your measurements. Compensation reduces the effects of sources of error between the device under test and the connection to the measuring instrument. Such errors result from test frequency, test voltage, impedance range, or other factors

Compensation is a three-step process:

Measuring the residual or "stray" capacitance between the test leads (in our illustrations, these are Kelvin test leads).

Performing an Open/Short correction

Performing a Load correction

Stray Capacitance

When a measurement is affected by a single residual component, the compensation is simple. Take the case of stray lead capacitance (Cstray) in parallel with the DUT capacitance (Cdut). The stray capacitance can be measured directly with no device connected.

When the device is connected, the actual DUT value can be determined by manually subtracting the stray capacitance (Cstray) from the measured value (Cmeasured).

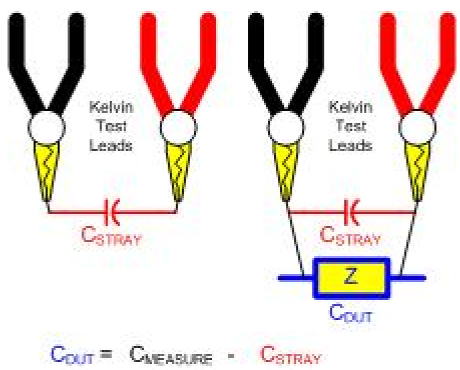


Figure 8. Stray Capacitance

Open/Short Correction

Open/Short correction is the most popular compensation technique. When the test leads are open, the residual admittance (Y) is measured. When the test leads are shorted, the residual impedance is measured. When the device is measured, these two residuals calculate the actual impedance of the DUT.

When performing an OPEN measurement, keep the distance between the test leads the same as they are when attached to the device.

WARNING: Do not touch or move your hands near the terminals.

When performing a SHORT measurement of high Z, connect a shorting device (shorting bar or highly conductive wire) between the terminals. For performing a SHORT measurement of low Z, connect the test leads directly together.

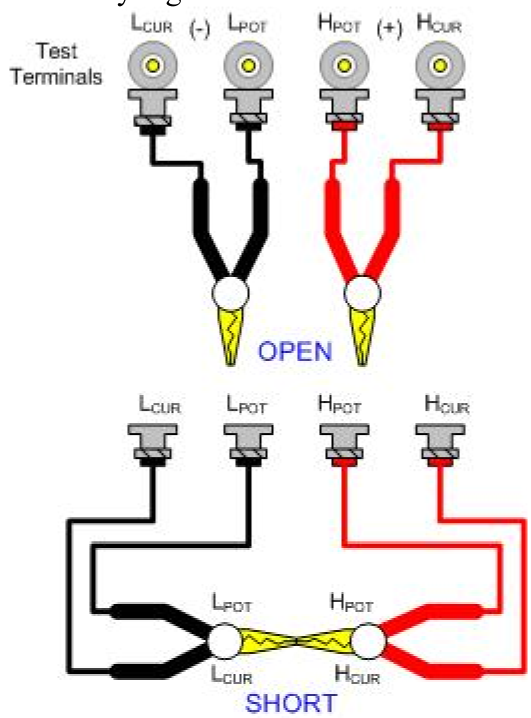


Figure 9. Open/Short

Load Correction

Load Correction uses an appropriate ("known good") load whose impedance was calculated in the first two steps. The data gathered from this load enables corrections to be applied to measurements of similar DUTs.

The appropriate load has the following properties:

Impedance value is accurately known.

Impedance value is close to the DUT's. (This ensures that the measuring instrument selects the same measurement range for both devices).

Impedance value is stable under the measurement conditions.

Physical properties allow using the same leads or fixture as the DUT.
A prerequisite for load correction is to perform a careful open/short correction. This feature, found on a number of IET Labs LCR Meters, provides for an automatic load correction. The load's known value is entered into memory, the load is measured, and the difference is then applied to ongoing measurements.

Z actual = Z measured ± delta Z where delta Z = the difference between the known and the measured value of the load.

7 Measurements of Capacitance

Capacitors are one kind of passive components used in electronic circuits. The basic construction of a capacitor is an insulating material, called dielectric, sandwiched between two electrodes. Capacitors are classified according to their dielectric material, which have a range of capacitance values according to their dielectric classification.

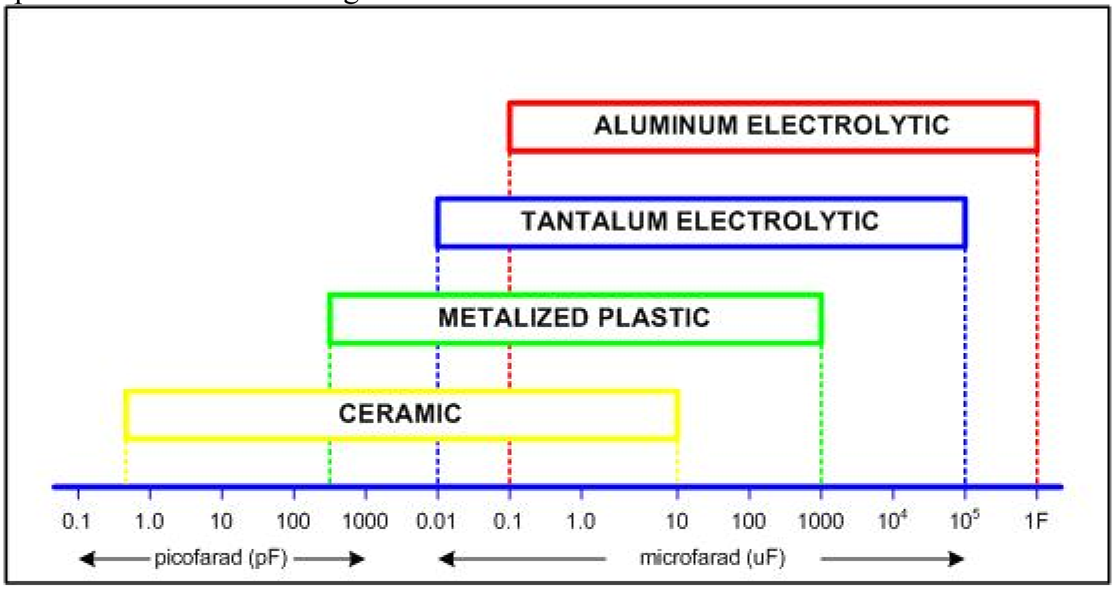


Figure 10. Dielectric Materials

Capacitance (C), dissipation factor (D), and equivalent series resistance (ESR) are the parameters usually measured.

Capacitance.....	The quantity of electrical charge that can be stored between the two electrodes.
Dissipation factor	Loss tangent. The ratio of energy lost to energy stored; the reciprocal of Q
ESR.....	A single resistive value of a capacitor representing all real losses. ESR is typically much larger than the series resistance of leads and contacts of the component. It includes effects of the capacitor's dielectric loss. ESR is related to D by the formula ESR = D/ωC where ω =2πf. ESR stands for equivalent series resistance, the same quantity that we call Rs in the above discussion. ESR is a measure of the loss in a capacitor and is related to D by:

ESR = Rs = D/ Cs (see Appendix A)

ESR is not equal to the resistance such as that of the connections or the foil or plate structure. It is a measure of the total loss in a capacitor: dielectric loss, leakage resistance, and loss in actual series resistance.

When the frequency is high or the capacitance is high, or both, the ESR often will approximate the actual series resistance because this resistance becomes the largest cause of loss under these conditions. However, ESR is always larger than this actual series resistance. ESR is a measure of the total "lossiness" of a capacitor. It is larger than Ras because the actual series resistance is only one source of the total loss (usually a small part).
At any frequency, a measure of complex impedance gives two numbers, the real part and the imaginary part: Z = Rs + jXs. At that frequency, the impedance behaves like a series combination of an ideal resistance Rs and an ideal reactance Xs. If Xs is negative, the impedance is capacitive and the reactance can be replaced with capacitance as shown in equation 8.

$$8: \quad Xs = \frac{-1}{\omega Cs}$$

We now have an equivalent circuit that is correct only at the measurement frequency. The resistance of this circuit is the equivalent series resistance:

ESR = Rs = Real part of Z

If we define the dissipation factor D as the energy lost divided by the energy stored in a capacitor we can deduce equation 9.

$$9: \quad D = \frac{\text{energy lost}}{\text{energy stored}}$$

$$= \frac{\text{Real part of Z}}{(\text{-Imaginary part of Z})}$$

$$= \frac{Rs}{(-)\ Xs}$$

$$= Rs\omega C$$

$$= (ESR)\ \omega C$$

If one took a pure resistance and a pure capacitance and connected them in series, then one could say that the ESR of the combination was indeed equal to the actual series resistance. However, when a pure resistance is connected in parallel with a pure capacitance to create a lossy capacitor, the ESR of the combination is the Real part of Z and the Real part of equation 10.

$$10: \quad \frac{1}{\frac{1}{Rp} + j\omega Cp} = \frac{Rp}{1 + \omega^2 Cp^2 Rp^2}$$

When there is no actual resistance in series with the capacitor, Ras = 0, and ESR > 0, therefore ESR > Ras.

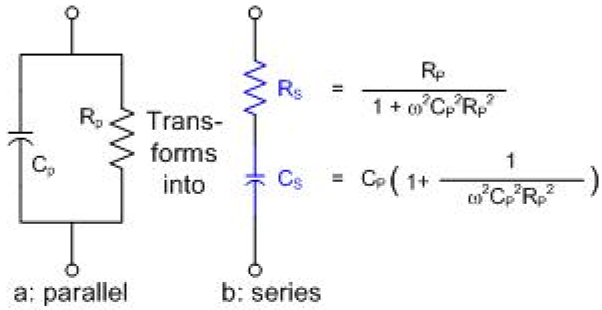


Figure 11. ESR

Series or Parallel

Generally a series equivalent circuit is a better model of a low-impedance circuit and a parallel equivalent circuit better models a high-impedance one. However, all physical components are, in effect, complicated networks containing resistance, capacitance and inductance. The best model should be the one whose parameter values change least as the frequency is changed in the range being used.

Advances in impedance measurement and capacitor manufacturing, coupled with a variety of applications have made the testing of capacitors somewhat complex. A typical equivalent circuit has C as capacitance, Rs as series resistance, L as inductance in lead wires and electrodes, and Rp represents the leakage between the capacitor electrodes.

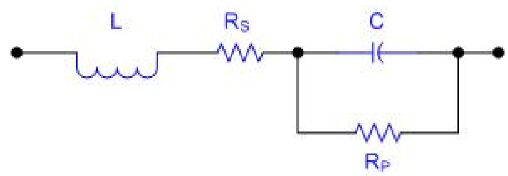


Figure 12. Equivalent Circuit for a Capacitor

Measuring a capacitor in series mode provides a different result than measuring in parallel mode. How they differ depends on Q (the ratio of energy stored to energy lost). Regardless of Q, the capacitor's measured value most closely represents its effective value when the more suitable equivalent circuit, series or parallel, is used. To determine which mode is best, consider the impedance magnitudes of the capacitive reactance, Rs and Rp. Reactance is inversely proportional to capacitance. In other words a small C yields large reactance, which means that the effect of parallel resistance (Rp) has a more significant effect than that of series resistance (Rs).

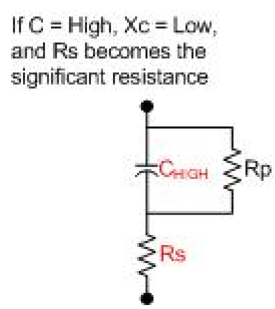


Figure 13. Low Capacitance Equivalent Circuit

The case of a large C, Rs is more significant than Rp, thus the series circuit mode is more appropriate. Mid-range values of C require a more precise comparison.

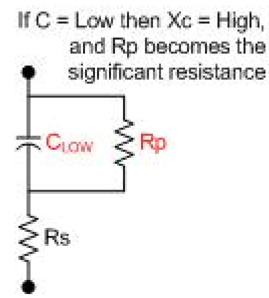
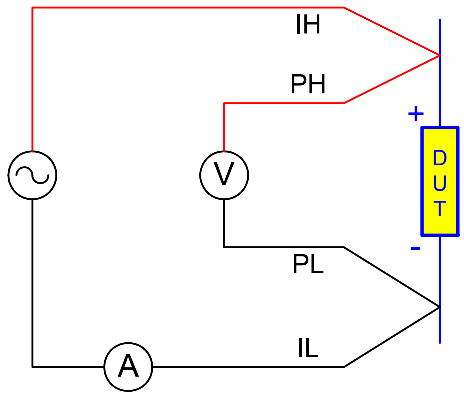


Figure 14. High Capacitance Equivalent Circuit

The rules of thumb for selecting the circuit mode should be based on the impedance of the capacitor:
Above approximately 10 kΩ use parallel mode
Below approximately 10Ω use series mode
Between these values, follow manufacturer's recommendation
Translated to a 1kHz test: Below 0.01 mF, use Cp mode; above 10 mF; use Cs mode; between these values use the manufacturer's recommendation.

Measuring Large and Small Values of Capacitance

Large values of capacitance represent relatively low impedances, so contact resistance and residual impedance in the test fixture and cabling must be minimized. The simplest form of connecting fixture and cabling is a two-terminal configuration but as mentioned previously, it can contain many error sources. Lead inductance, lead resistance and stray capacitance between the leads can alter the result substantially. A three-terminal configuration, with coax cable shields connected to a guard terminal, reduces effects of stray capacitance. Because the lead inductance and resistance still remains, this is a help to small-value capacitors but not to the large-value capacitors.



For the best of both worlds a four-terminal connection (often termed Kelvin), shown in reduces the effects of lead impedance for large-value capacitors.

Two of the terminals for current sourcing to the DUT, and two for voltage sensing. This technique removes errors resulting from series lead resistance and provides considerable advantage in low-impedance situations.

Figure 15. Diagram of Kelvin Connection

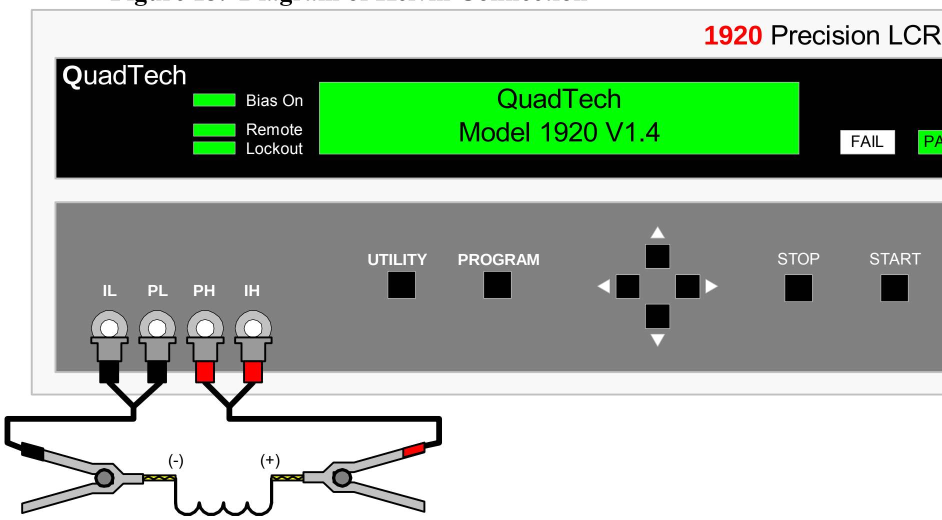


Figure 16. Functional Kelvin

Besides a four-terminal connection made as close as possible to the DUT, a further enhancement is an OPEN/SHORT compensation by the measuring instrument. The open/short compensation subtracts (“zeroes out”) the effects of stray mutual inductance between test connections and lead inductance. (The effect of lead inductance increases the apparent value of the capacitance being measured.) Through OPEN/SHORT compensation, each residual parameter can be measured and the value of a DUT automatically corrected.
Aim toward consistency in techniques, instruments, and fixtures. This means using the manufacturer’s recommended 4-terminal test leads (shielded coax) for the closest possible connection to the DUT. The OPEN/SHORT should be performed with a true open or short at the test terminals. For compensation to be effective, the open impedance should be 100 times more than the DUT impedance and the short impedance 100 times less than the DUT impedance. Of equal importance, when performing open/short zeroing, the leads must be positioned exactly as the device under test expects to see them.

8 Measurements of Inductance

SAFETY FIRST

Since it is possible to apply large values of current and voltage to an inductor, WARNING: when the current through an inductive circuit is suddenly interrupted, **the voltage can increase to potentially lethal levels.** If a person breaks the contact without the proper protection, the inductor induces a high voltage, forcing the current through the person.

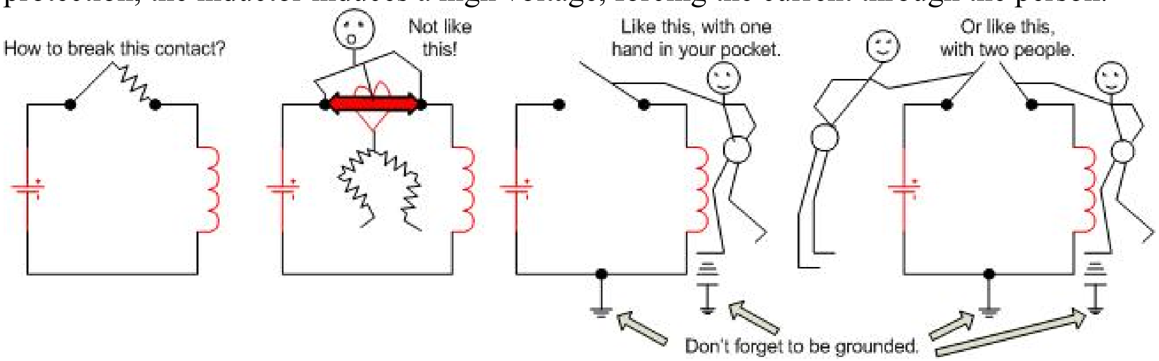


Figure 17. Safely Breaking Contact

An inductor is a device for storing energy in a magnetic field. A capacitor is a device for storing energy in an electric field. An inductor consists of wire coiled around a core material. Air is the simplest core material for inductors because it is constant, but for physical efficiency, magnetic materials such as iron and ferrites are commonly used. The core material of the inductor, its' length and number of turns directly affect the inductor's ability to carry current.

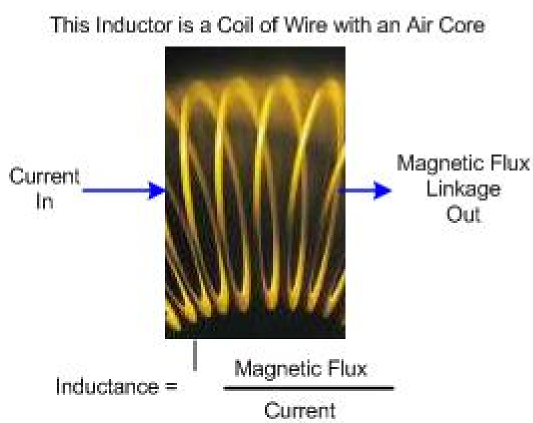


Figure 18. Inductor Defined

Series or Parallel

As with capacitors, inductor measurements can be made in either a series or parallel mode. In a typical equivalent circuit for an inductor, the series resistance (Rs), represents loss of the copper wire and parallel resistance (Rp) represents core losses.

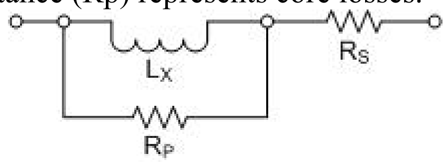


Figure 19. Inductor Circuit

In the case where the inductance is large, the reactance at a given frequency is relatively large, so the parallel resistance becomes more significant than any series resistance, hence the parallel mode should be used. For very large inductance a lower measurement frequency will yield better accuracy.

For low value inductors, the reactance becomes relatively low, so the series resistance is more significant, thus a series measurement mode is appropriate. For very small inductance a higher measurement frequency will yield better accuracy. For mid range values of inductance a more detail comparison of reactance to resistance should be used to help determine the mode.

Whenever a problem occurs in measurement correlation, use the test conditions specified by the component manufacturer. Independent of any series/parallel decision, it is common for different LCR meters to give different measured results. One good reason for this is that inductor cores can depend on the test signal. If the programmed output voltages are different, the measured inductance will likely be different.

Even if the programmed output voltage is the same, two meters can still have a different source impedance. A difference in source impedance can result in a difference in current to the device, and once again, a different measured value.

Inductance Measurement Factors

Here are four factors for consideration in measuring actual inductors:

DC Bias Current

Constant Voltage (Voltage Leveling)

Constant Source Impedance

DC Resistance & Loss

There are other considerations such as core material and number of coils (turns) but those are component design factors not measurement factors.

DC Bias Current

To measure inductance accurately, the inductor must be tested under actual (real life) conditions for current flowing through the coil. As the typical source in an LCR meter supplies small amounts of current (<1mA), this cannot always be accomplished. Inductors used in power supplies need a larger current supply. Instead of using a larger AC current source, inductors are usually tested with a combination of DC current and AC current. DC bias current provides a way of biasing the inductor to normal operating conditions where the inductance can then be measured with a normal LCR meter. The bottom line: that the measured inductance is dependent on the current flowing through the inductor.

Constant Voltage (Voltage leveling)

Since the voltage across the inductor changes with impedance of the inductor and the impedance of the inductor changes with current, a typical LCR meter designed for measurements on capacitive and resistive devices can cause the inductance to appear to drift. The actual inductance is not drifting but is caused by the voltage across the inductor continuously changing, so the current is not constant. A voltage leveling circuit monitors the voltage across the inductor and continually adjust the programmed source voltage in order to keep the voltage across the inductor constant.

Constant Source Impedance

The current flowing through the inductor from the AC source in the LCR meter must be held constant. If the current is not held constant the inductance measurements will change. This change is generally a function of the LCR meter's open circuit programmed test voltage. The programmed voltage in an LCR meter is obtained under an open circuit condition. A source resistance (Rs, internal to the meter) is effectively connected in series with the AC output and there is a voltage drop across this resistor. When a test device is connected, the voltage applied to the device depends on the value of Rs and the impedance value of the device. The source impedance is normally between 5Ω and 100kΩ.

DC Resistance and Loss

Measuring the DCR or winding resistance of a coil of wire confirms that the correct gauge of wire, tension and connection were used during the manufacturing process. The amount of opposition or reactance a wire has is directly proportional to the frequency of the current variation. That is why DC resistance is measured rather than AC. At low frequencies, the DC resistance of the winding is equivalent to the copper loss of the wire. Knowing a value of the wire's copper loss can provide a more accurate evaluation of the total loss (D) of the device under test (DUT).

Loss: Copper, Eddy Current, and Hysteretic

Three possible sources of loss in an inductor measurement are copper, eddy-current and hysteretic. They are dependent on frequency, signal level, core material and device heating. As stated above, copper loss at low frequencies is equivalent to the DC resistance of the winding. Copper loss is inversely proportional to frequency. (As frequency increases, the copper loss decreases.) Copper loss is typically measured using an inductance analyzer that measures DC resistance rather than an AC signal.

Eddy-Current Loss in iron and copper are due to currents flowing within the copper or core caused by induction. The result of eddy-currents is a loss due to heating within the inductors copper or core. Eddy-current losses are directly proportional to frequency.

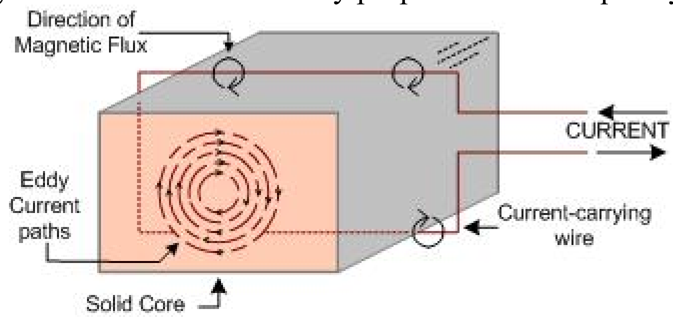
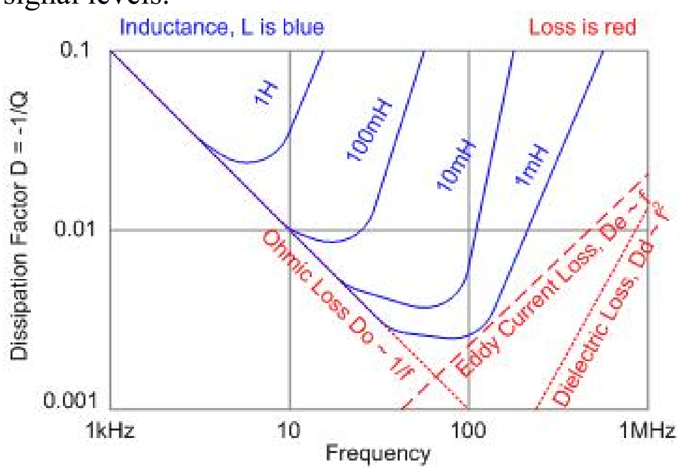


Figure 20. Eddy Currents

Hysteretic Loss is proportional to the area enclosed by the hysteretic loop and to the rate at which this loop transverses (i. e., the frequency). It is a function of signal level and increases with frequency. Hysteretic loss is however independent of frequency. The dependence upon signal level does mean that for accurate measurements it is important to measure at known signal levels.



$$D \simeq \frac{1}{1 - \left(\frac{f}{f_r}\right)^2}\left[\frac{R_o}{\omega L_o} + G_e \omega L_o + \left(\frac{f}{f_r}\right)^2 D_o\right]$$

Figure 21. Dissipation Factor

9 Measurements of Resistance

Of the three basic circuit components, resistors, capacitors and inductors, resistors cause the fewest measurement problems. This is true because it is practical to measure resistors by applying a DC signal or at relatively low AC frequencies. In contrast, capacitors and inductors always experience AC signals that by their very nature are prone to fluctuation, thus these components are generally measured under changing conditions. Resistors are usually measured at DC or low frequency AC where Ohm's Law gives the true value under the assumption that loss factors are accounted for. However, when resistors are used in high frequency circuits they will have both real and reactive components. This can be modeled with a series inductance (Ls) and parallel capacitance (Cp).

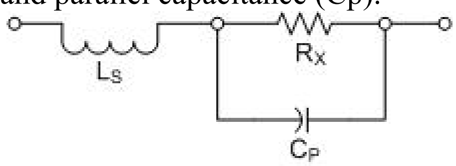


Figure 22. Resistor Circuit

For example, in the case of a wire-wound resistor (which sounds like an inductor) it's easy to understand how windings result in this L term. Even though windings can be alternately reversed to minimize the inductance, the inductance usually increases with resistance value (because of more turns). In the case of carbon and film resistors, conducting particles can result in a distributed shunt capacitance, thus the C term.

Series or Parallel

So how does one choose the series or parallel measurement mode? **For low values** of resistors (below 1kΩ) the choice usually becomes a low frequency measurement in a series equivalent mode. Series because the reactive component most likely to be present in a low value resistor is series inductance, which has no effect on the measurement of series R. To achieve some degree of precision with low resistance measurements it is essential to use a four-terminal connection.

This technique actually eliminates lead or contact resistance which otherwise could elevate the measured value. Also, any factor that affects the voltage drop sensed across a low resistance device will influence the measurement. Typical factors include contact resistance and thermal voltages (those generated by dissimilar metals). Contact resistance can be reduced by contact cleanliness and contact pressure.

For high values of resistors (greater than several MΩ) the choice usually becomes a low frequency measurement in a parallel equivalent mode. Parallel because the reactive component most likely to be present in a high value resistor is shunt capacitance, which has no effect on the measurement of parallel R.

10 Measurements of Impedance

IET Labs manufactures several instruments for the measurement and analysis of passive components. The 7600 Series LCR Meter is an automatic instrument designed for the precise measurement of resistance, capacitance and inductance parameters and associated loss factors. It is also suited for use in calibration and standards laboratories and can assume many tasks previously performed by manually balanced impedance bridges and meters.

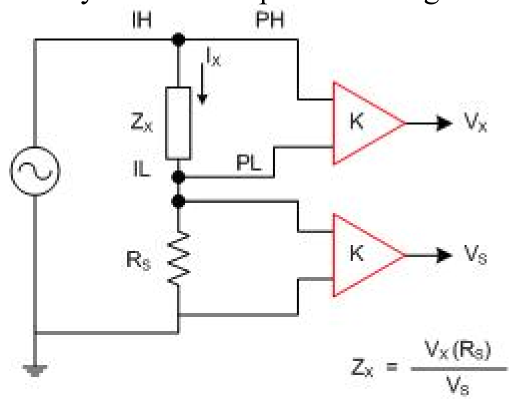


Figure 23. 7600 Measurement Circuit

The measurements of highest precision in a standards lab are 1:1 comparisons of similar impedance standards, particularly comparisons of standards calibrated at the National Institute of Standards and Technology (NIST). This type of measurement requires an instrument with high resolution and repeatability in order to detect parts-per-million (ppm) differences. In such applications, two standards of very nearly equal value are compared using "direct substitution"; they are measured sequentially and only the difference between them is determined.

The resolution of the 7600 is 0.1 ppm for the direct measured values and such direct reading measurements, at a one/second rate, have a typical standard deviation of 10 ppm at 1 kHz. By using the instrument's AVERAGING mode, the standard deviation can be reduced by $1/\sqrt{N}$, where N is the number of measurements. Thus, an average of 5 measurements reduces the standard deviation to 5 ppm. It is therefore possible to measure the difference between two impedances to approximately 10 ppm.

Precision can be further improved by using the 7600's median measurement mode. In the median measurement mode, the instrument makes three measurements and discards the high and low results. The remaining median measurement value is used for display or further processing (such as averaging). A combination of averaging and median measurements increases precision, yielding measurements independent of errors caused by line spikes or other non-Gaussian noise sources.

The ppm resolution of the 7600 is not limited to values near full scale. In the case of a manually balanced bridge, the resolution of a six-digit reading of 111111 is 9 ppm. The 7600 has the same 0 .1 ppm resolution at all values of all parameters including dissipation factor (D) and quality factor (Q).

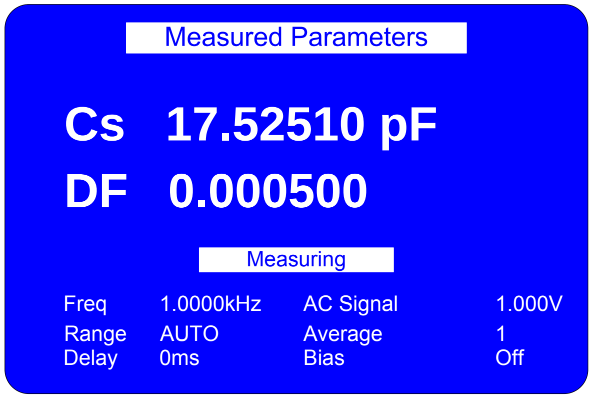


Figure 24. Parts Per Million Resolution

The 7600 Plus IET Labs instrument provides for load correction, allowing the user to enter known values for both primary and secondary parameters. The instrument measures these parameters and automatically applies the correction to ongoing measurements.

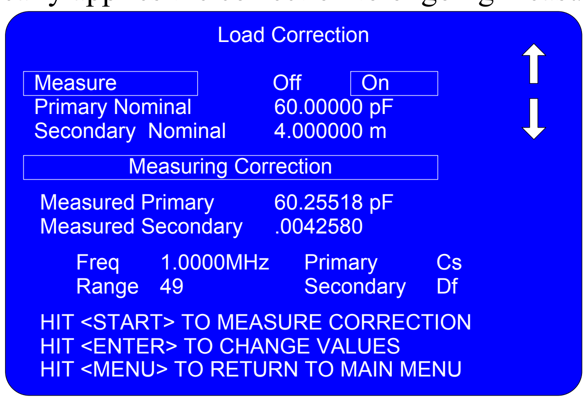


Figure 25. Entry of Values for Load Correction

Since a balancing procedure is not required, an automated instrument is faster.
Another advantage of programmable instruments is their integration into the instrument's RS-232 and IEEE-488.2 bus interfaces. With a computer based system, correction calculations can be made without the opportunity for human errors.

Accuracy

Accuracy of a measurement depends on the calibration procedure of the instrument, its basic accuracy, and its actual accuracy.

Basic Accuracy

Manufacturers of LCR meters specify basic accuracy. This is the best-case accuracy that can be expected without accounting for error due to fixtures or cables.

The basic accuracy is specified at optimum test signal, frequencies, highest accuracy setting or slowest measurement speed, and impedance of the DUT. As a general rule this means 1VAC RMS signal level, 1kHz frequency, 1 measurement/second, and a DUT impedance between 10Ω and 100k Ω. Typical LCR meters have a basic accuracy between ±0.01% and ±0.5%.

Actual Accuracy

Actual accuracy refers to measurements made in the day-to-day world. This is done using a formula or by looking at a graph of accuracy versus impedance and frequency.
The measurement range is really more a display range. For example, an LCR will specify a measurement range of 0.001nH to 99.999H, but this does not mean you can accurately measure a 0.001nH inductor or a 99.9999H inductor. Rather, it means that when you perform a measurement the display resolution will go down to 0.001nH or up to 99.999H. This is really why it is important to check the accuracy of the measurement you want to perform. Do not assume that just because the value you want to measure is within the measurement range you can accurately measure it.
The accuracy formulas take into account each of the conditions effecting accuracy. Most common are measurement range, accuracy/speed, test frequency and voltage level.

Factors Affecting the Accuracy of Measurements

DUT Impedance
Because it is difficult to measure the current flowing through the DUT, high impedance measurements increase the rate of error. For example, if the impedance is greater than 1MΩ and the test voltage is one volt there will be less than 1mA of current flowing through the DUT.
Because it is difficult to measure the voltage across the DUT, low impedance measurements have an increase in the rate of error. Most LCR meters have an internal source resistance of 100k to 5 Ω in series with the source. As the impedance of the DUT, approaches the internal source resistance of the meter, the voltage across the DUT drops proportionally.
When the impedance of the DUT is significantly less than the internal source resistance, the voltage across the DUT becomes extremely small, increasing the rate of error.
Frequency
The impedance of reactive components is proportional to frequency, which affects accuracy. For example, measurement of a 1mF capacitor at 1 kHz would be within basic measurement accuracy; the same measurement at 1MHz would have significantly more error due to the decrease in the impedance of a capacitor at high frequencies.
Resolution
Resolution must also be considered for low value measurements. If trying to measure 0.0005 Ω and the resolution of the meter is 0.00001 Ω, the accuracy of the measurement cannot be any better than ±2%.
Accuracy and Speed
Accuracy and speed are inversely proportional. That is the more accurate a measurement the more time it takes. LCR meters will generally have 3 measurement speeds. Measurement

speed can also be referred to as measurement time or integration time. Basic accuracy is always specified with the slowest measurement speed, generally 1 second for measurements above 1kHz. At lower frequencies measurement times can take even longer because the measurement speed refers to one complete cycle of the stimulus voltage. For example, if measurements are to be made at 10Hz, the time to complete one cycle is 1/frequency = 1/10Hz = 100 milliseconds. Therefore the minimum measurement speed would be 100ms.
Dissipation Factor (D) or Quality Factor (Q)
D and Q are reciprocals. The importance of D and Q is that they represent the ratio of resistance to reactance and vice versa. The ratio Q represents the tangent of the phase angle. As phase is another measurement that an LCR meter must make, this error needs to be considered. When the resistance or reactance is much much greater than the other, the phase angle will approach ±90° or 0°. Even small changes in phase at -90° result in large changes in the value of resistance, R.

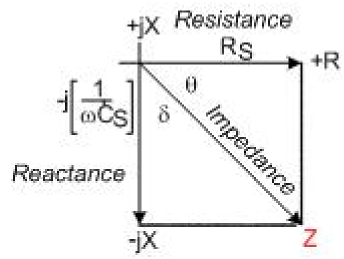


Figure 26. Capacitance Phase Diagram

Example: Accuracy Formula for 7600 Plus Precision LCR Meter

Test Conditions:
1pF Capacitor at 1MHz
1VAC signal
Auto Range
Non-Constant Voltage
Slow Measurement Speed
D = 0.001
Basic Accuracy of the 7600 = ±0.05%
Accuracy Formula for Slow Mode R, L, C, X, G, B, |Z|, and |Y| is given in Equation 11.

Vs = Test voltage in voltage mode,
= I * Zm in current mode*
Zm = Impedance of DUT
Fm = Test frequency
Kt = 1 for 18º to 28ºC
= 2 for 8º to 38ºC
= 4 for 5º to 45ºC
VFS = 5.0 for 1.000V < Vs ≤ 5.000V

1.0 for 0.100V < Vs ≤ 1.000V

0.1 for 0.020V ≤ Vs ≤ 0.100V
For Zm > 4* Z_{RANGE} multiply A% by 2
For Zm > 16* Z_{RANGE} multiply A% by 4
For Zm > 64* Z_{RANGE} multiply A% by 8
(For I * Zm > 3, accuracy is not specified)
The impedance range (Z_{RANGE}) is specified in this table:

	In Voltage Mode	In Current Mode
Z_{RANGE} =	100kΩ for Zm ³ 25kΩ	400Ω for I < 2.5mA
	6kΩ for 1.6kΩ ≤ Zm < 25kΩ	25Ω for I > 2.5mA
	6kΩ for Zm > 25kΩ and Fm > 25kHz	
	400Ω for 100Ω ≤ Zm < 1.6kΩ	
	400 Ω for Zm > 1.6k Ω and Fm > 250kHz	
	25 Ω for Zm < 100 Ω	

Substituting the values listed here, the Calculated Accuracy, using the formula in equation 11 is 3.7%.

Kt = 1
Zm = 1/(2π*frequency*C)
= 1/(2π*1000000*1x10-12)
= 159 kΩ
Z_{RANGE} = 400 Ω
Vfs = 1
Multiply A% = 8
A% = 0.46%
Multiply A% times 8 due to Zm > 64 times Z_{RANGE}
A% = 0.46% * 8 = 3.68%

$$A\% = \pm\left[0.025 + \left(\left(0.025 + \frac{.05}{|159000|}\right) + \left(|159000| \times 10^{-7}\right)\right) \times \left(\frac{.2}{1} + .8 \times \frac{1}{1} + \frac{(1-1)^2}{4}\right) \times \left(0.7 + \frac{1000000}{10^5} + \frac{300}{1000000}\right)\right] \times 1$$

Example Accuracy Graph

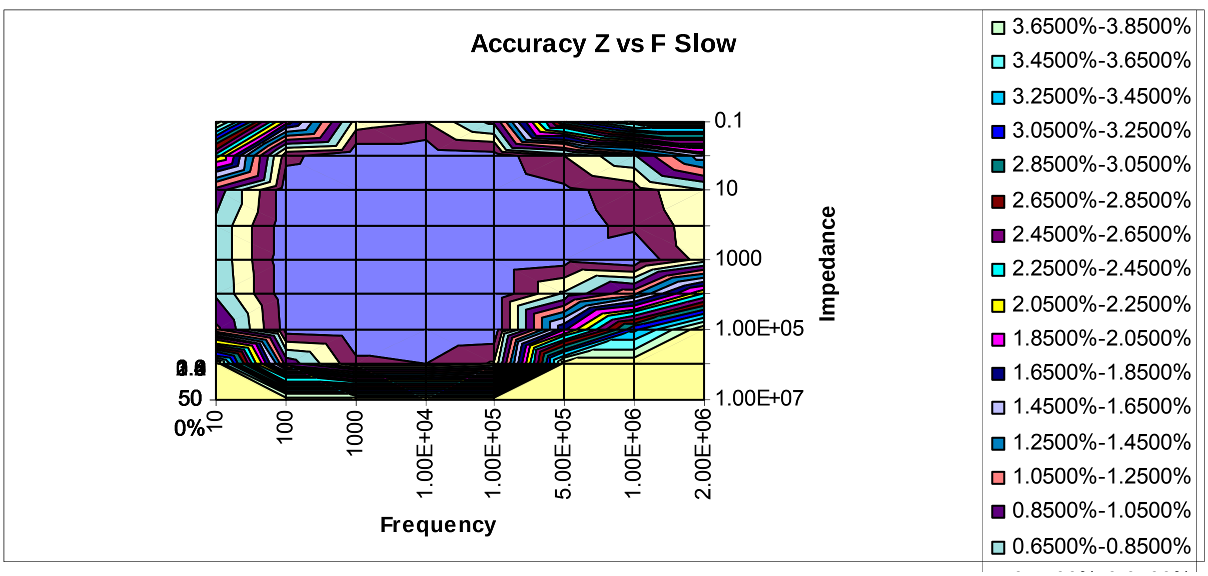


Figure 27. Graph: Z Accuracy vs. F Slowness

The accuracy could have been predicted without the use of a formula. If we calculate the impedance of a 1pF capacitor at 1MHz we get a value of:
Z = Xs = 1/(2πfC)

$Z = Xs = 1/(2\pi*1{,}000{,}000*0.000{,}000{,}000{,}001) = 159k\Omega$

In the graph, substitute Z for R. If we find the position on the graph for an impedance value of 159kΩ at 1MHz we see a light blue or teal representing an accuracy of 3.45% to 3.65%. Overall the graph and formula point to the same accuracy of ±3.5%.

11 Dielectric Constant Measurement of Solids and Liquids

Many materials have unique sets of electrical characteristics which are dependent on its dielectric properties. Precision measurements of these properties can provide valuable information in the manufacture or use of these materials. Herein is a discussion of dielectric constant and loss measurement methods.

There are many different notations used for dielectric properties. This discussion will use K, the relative dielectric constant, and D, the dissipation factor (or tan δ) defined as follows:

$$K = \varepsilon' = \varepsilon_r$$

and

$$D = \tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'}$$

The complex relative permittivity is:

$$\varepsilon_r^* = \frac{\varepsilon}{\varepsilon_o} = \varepsilon_r' - j(\varepsilon_r'')$$

where ε_0 is the permittivity of a vacuum, and ε the absolute permittivity.

$$\varepsilon_o = 0.08854\text{pF/cm}$$

The capacitance of a parallel-plate air capacitor (two plates) is:

$$C = K_a\ \varepsilon_o\ \text{Area / spacing}$$

where Ka is the dielectric constant of air:

$$K_a = 1.00053$$

if the air is dry and at normal atmospheric pressure.

Measurement Methods, Solids: The Contacting Electrode Method

This method is quick and easy, but is the least accurate. The results for K should be within 10% if the sample is reasonably flat. The sample is first inserted in the cell and the electrodes closed with the micrometer until they just touch the sample. The electrodes should not be forced against the sample. The micrometer is turned with a light finger touch and the electrometer setting recorded as h_m.

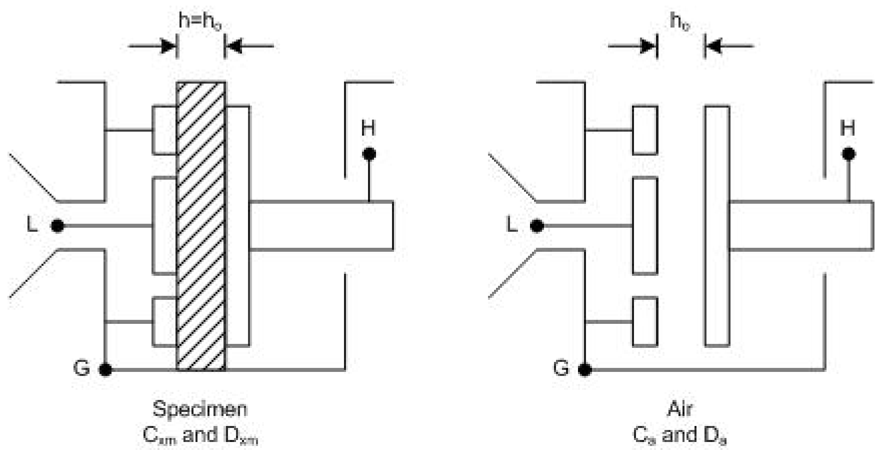


Figure 28. Contact Electrode

The LCR Meter should be set to measure parallel capacitance and the capacitance and dissipation factor of the sample measured as C_{xm} and D_{xm}.

The electrodes are opened and the sample removed and then the electrodes closed to the same micrometer reading, h_m. C (parallel) and D of empty cell are measured as C_a and D_a.

Calculate K_x and D_x of the sample from:

$$K_x = (1.0005)\left(\frac{C_{xm}}{C_a}\right)$$

and

$$D_x = (D_{xm} - D_a)$$

The factor 1.0005 in the formula for K_x corrects for the dielectric constant of (dry) air. Subtracting D_a from D_{xm} removes any constant phase error in the instrument. For even better D accuracy, the electrode spacing can be adjusted until the measured capacitance is approximately equal to C_{xm}, and then D_{xm} measured.

Note that both K_x and D_x will probably be too low because there is always some air between the electrodes and the sample. This error is smallest for very flat samples, for thicker samples and for those with low K and D values.

Air-Gap Method

This method avoids the error due to the air layer but requires that the thickness of the sample is known. Its thickness should be measured at several points over its area and the measured values should be averaged to get the thickness h. The micrometer used should have the same units as those of the micrometer on the cell.

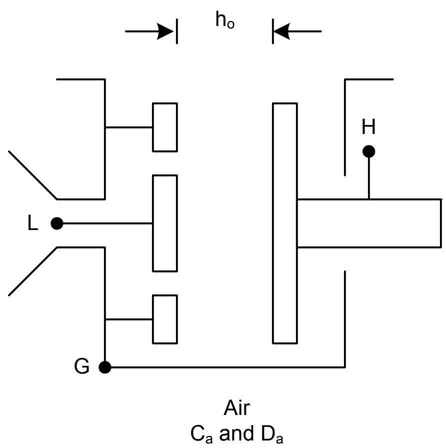


Figure 29. Air-Gap Method

The electrodes are set to about .02 cm or .01 inch greater than the sample thickness, h, and the equivalent series capacitance and D measured as Ca and Da. Note the micrometer setting as hm, which can be corrected with the micrometer zero calibration, hmo, to get the following:

$$h_o = (h_m + h_{mo})$$

The sample is inserted and measured as Cxa and Dxa. Calculate:

$$M = \frac{(h_o - h)}{h_o}$$

$$D = (D_{xa} - D_a)\left(\frac{C_a}{C_a - MC_{xa}}\right)$$

$$K_x = \left(\frac{(1-M)\,C_{xa}}{C_a - MC_{xa}}\right)\left(\frac{1.0005}{1 + D_x^2}\right)$$

The factor (1 + Dx2) converts the series value of Cx to the equivalent parallel value and is not necessary if Dx is small. The factor of 1.0005 corrects for the dielectric constant of air (if dry). The formula for Dx assumes that the true D of air is zero and it makes a correction for a constant D error in the instrument.

Two-Fluid Method

This method is preferred for specimens whose thickness is difficult to measure and for best accuracy which will be limited by the accuracy of the C and D measurements. However it requires four measurements, two using a second fluid (the first being air). The dielectric properties of this fluid need not be known, but it must not react with the specimen and it must be stable and safe to use. A silicone fluid such as Dow Corning 200, 1 centistoke viscosity, is most generally satisfactory.

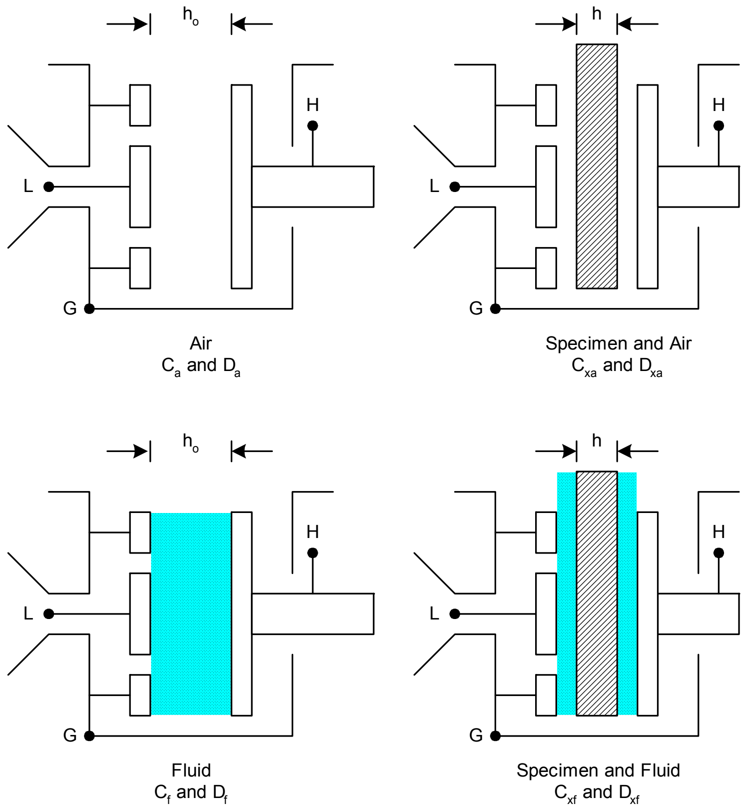


Figure 30. Two-Fluid Method

Spacing is the same for all measurements and should be just slightly more than the specimen thickness. The accuracy will be limited mainly by the accuracy of the measurements made. From these measurements calculate:

$$\frac{h}{h_o} = 1 - \frac{C_a C_f \ (C_{xf} - C_{xa})}{C_{xa} C_{xf} \ (C_f - C_a)}$$

$$\frac{C_{xser}}{C_a} = \frac{C_{xf} \ C_{xa} \ (C_f - C_a)}{C_a \ (C_{xa} C_f - C_{xf} C_a)}$$

which is the ratio of the equivalent series capacitance of the sample to Ca.
If Dx is close to Dxf or larger use:

$$D_x = D_{xf} + \frac{C_a \ (C_{xf} - C_{xa})(D_{xf} - D_f)}{(C_{xa} C_f - C_{xf} C_a)}$$

If Dx is very small, use:

$$D_x = \frac{(D_{xa} - D_a) \ C_{xf} \ (C_f - C_a)}{(C_{xa} C_f - C_{xf} C_a)}$$

to make a zero D correction. From the above results calculate:

$$K_x = \left(\frac{h}{h_o}\right)\left(\frac{C_{xser}}{C_a}\right)\left(\frac{1.0005}{1 + D_x^2}\right)$$

As before, the factor of 1.0005 corrects for the dielectric constant of air (if dry) and the factor (1 + Dx2) converts Cx to equivalent parallel capacitance.

Measurement Methods, Liquids

Measurements on liquids are simple—the only difficulty is with handling and cleanup. Equivalent parallel capacitance and D of air (Ca and Da), is measured first and then that of the liquid (Cxm and Dxm)
Determine Kx and Dx:

$$K_x = \left(\frac{C_{xm}}{C_a}\right)\left(1.0005\right)$$

$$D_x = (D_{xm} - D_a)$$

Note: Spacing is not critical but should be narrow enough to make the capacitance large enough to be measured accurately.

12 What an LCR Meter Should Do

As with most test instrumentation, LCR meters can come with a host of bells and whistles but the features one most often uses are described herein.

Test Frequency

Electrical components need to be tested at the frequency for which the final product/application will be utilized. An instrument with a wide frequency range and multiple programmable frequencies provides this platform.

Test Voltage

The ac output voltage of most LCR meters can be programmed to select the signal level applied to the DUT. Generally, the programmed level is obtained under an open circuit condition. A source resistance (Rs, internal to the meter) is effectively connected in series with the ac output and there is a voltage drop across this resistor. When a test device is connected, the voltage applied to the device depends on the value of the source resistor (Rs) and the impedance value of the device.

Accuracy/Speed

Classic trade-off. The more accurate your measurement the more time it takes and conversely, the faster your measurement speed the less accurate your measurement. That is why most LCR meters have three measurement speeds: slow, medium and fast. Depending on the device under test, the choice is yours to select accuracy or speed.

Measurement Parameters

Primary parameters L, C and R are not the only electrical criteria in characterizing a passive component and there is more information in the Secondary parameters than simply D and Q. Measurements of conductance (G), susceptance (B), phase angle (q) and ESR can more fully define an electrical component or material.

Ranging

In order to measure both low and high impedance values measuring instrument must have several measurement ranges. Ranging is usually done automatically and selected depending on the impedance of the test device. Range changes are accomplished by switching range resistors and the gain of detector circuits. This helps maintain the maximum signal level and highest signal-to-noise ratio for best measurement accuracy. The idea is to keep the measured impedance close to full scale for any given range, again, for best accuracy.

Averaging

The length of time that an LCR meter spends integrating analog voltages during the process of data acquisition can have an important effect on the measurement results. If integration occurs over more cycles of the test signal the measurement time will be longer, but the accuracy will be enhanced. This measurement time is usually operator controlled by selecting a FAST or SLOW mode, SLOW resulting in improved accuracy. To enhance accuracy, the measurement averaging function may be used. In an averaging mode many measurements are made and the average of these is calculated for the end result.

Median Mode

Accuracy can be enhanced by employing the median mode function. In a median mode 3 measurements might be made and two thrown away (the lowest and the highest value). The median value then represents the measured value for that particular test.

Computer Interface

Many testers today must be equipped with some type of communication interface for remote data processing, computer or remote control. For an operation retrieving only pass/fail results the Programmable Logic Control (PLC) is often adequate, but for data logging it's a different story. The typical interface for this is the IEEE-488 general purpose interface bus or the RS-232 serial communication line.

These interfaces are commonly used for monitoring trends and process control in a component manufacturing area or in an environment where archiving data for future reference is required. For example when testing 10% components, the yield is fine when components test at 8% or 9%, but it does not take much of a shift for the yield to plummet. The whole idea of production monitoring is to reduce yield risks and be able to correct the process quickly if needed. An LCR Meter with remote interface capability has become standard in many test applications where data logging or remote control have become commonplace.

Display

An instrument with multiple displays provides measured results by application at the press of a button. Production environments may prefer a Pass/Fail or Bin Summary display. R&D Labs may need a deviation from nominal display. The 7600 series instruments have seven display modes: measured parameters, deviation from nominal, % deviation from nominal, Pass/Fail, Bin Summary, Bin Number and No Display.

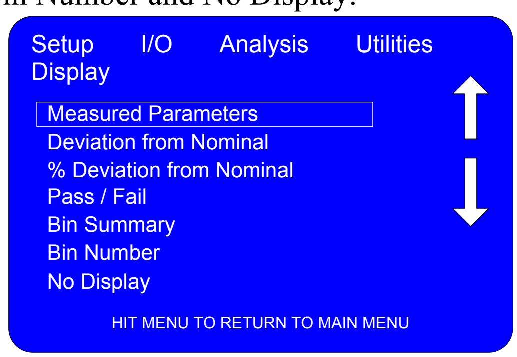


Figure 31. Display Menu

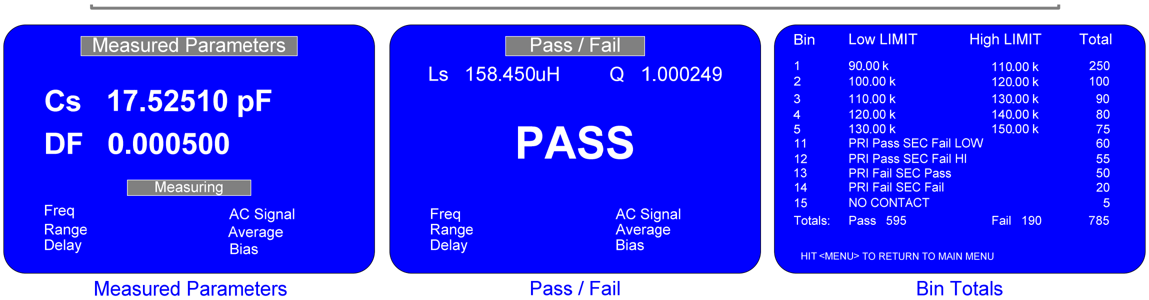


Figure 32. 7600 Plus Display Modes

Binning

A necessary production application, binning sorts components by test results quickly by a predetermined value set by the test engineer. Two of the most common methods of sorting results into bins are using nested limits or sequential limits.

Nested Limits

Nested limits are a natural choice for sorting components by % tolerance around a single nominal value with the lower bins narrower than the higher numbered bins. Nested limits for three bins are illustrated. Limits can be asymmetrical (Bin 3 is -7% and +10%).

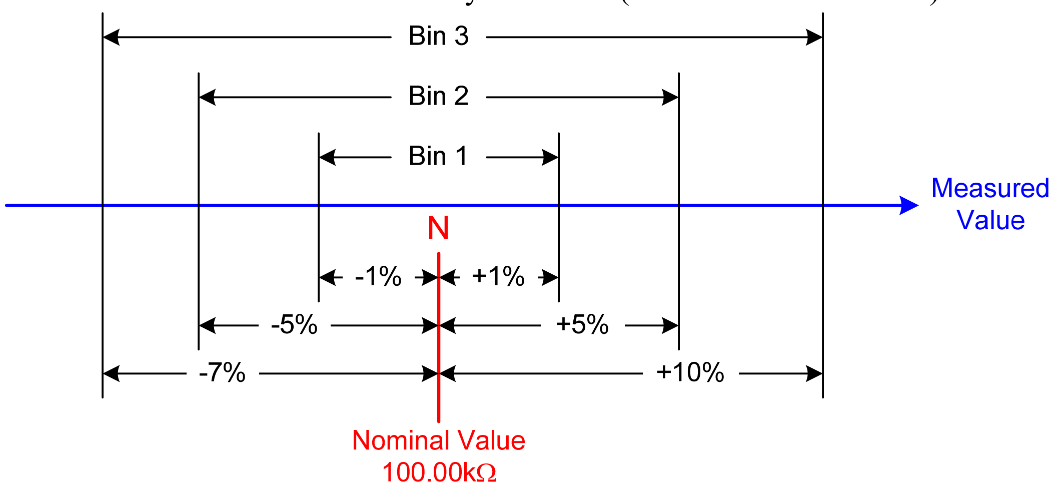


Figure 33. Nested Limits

Sequential Limits

Sequential limits are a natural choice when sorting components by absolute value. Sequential bins do not have to be adjacent. Their limits can overlap or have gaps depending upon the specified limit. Any component that falls into an overlap between bins would be assigned to the lower numbered bin and any component that falls into a gap between bins would be assigned to the overall fail bin.

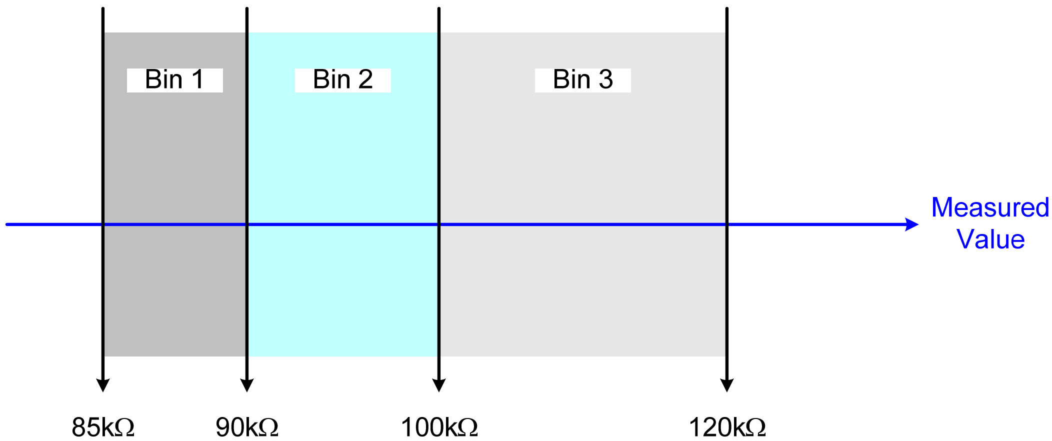


Figure 34. Sequential Limits

Test Sequencing

A sequence of tests, each with different test parameters and conditions can be performed on a single component. Combined with the binning process, test sequencing enables multiple tests on a single component and then sorting by test. This is a great electrical characterization tool for finding out under which conditions your particular component fails.

Parameter Sweep

Another excellent device characterization tool of LCR meters is the parameter sweep function. A sweep is a user-defined number of measurements for a particular test. The IET Labs 7600 Series instruments display a table or plot of measured results versus a test variable such as frequency, voltage or current. The user defines the lower boundary of the sweep in Hz, Volts or Amps; the upper boundary in Hz, Volts or Amps; the step or number of increments in the sweep and the format (table or plot).

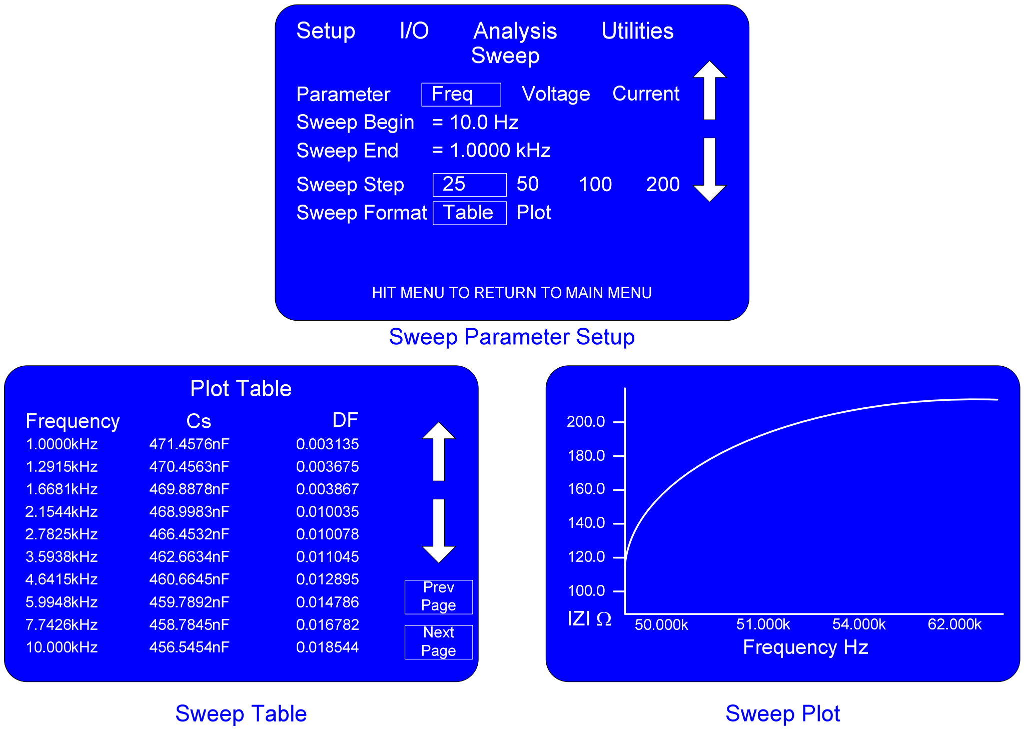


Figure 35. Parameter Sweep Function

Bias Voltage and Bias Current

A bias voltage or bias current function enables real time operating conditions to be applied to the device under test. Bias an inductor with DC current of 1-2mA to simulate the current running through it in its real application (such as in a power supply).

Constant Source Impedance

An LCR meter with constant source impedance, it provides a source resistance (Rs) that will hold the current constant. Therefore one knows what the voltage at the DUT will be. Rs is in series with the ac output such that the programmed voltage is 1V but the voltage to the test device is 0.5V.

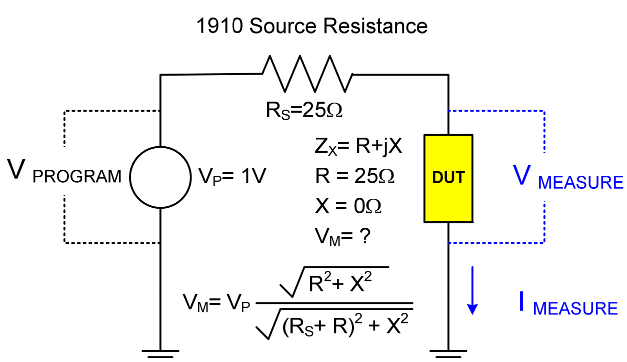


Figure 36. Constant Source Impedsnce

Monitoring DUT Voltage & Current

Monitoring the voltage across or current through the DUT during test enables real time analysis of the device. If the voltage can be kept level (constant) across a DUT then the impedance can be measured accurately. In inductor measurements it is necessary to keep the voltage across the inductor constant because the voltage across an inductor changes with the impedance of the inductor which changes with the current through it. So the ability to monitor the voltage and current to the DUT will provide the most accurate conditions for impedance measurement.

13 Examples of Precision LCR Meters

DE 5000 Handheld LCR Meter

- Test Frequency: 100 Hz / 120 Hz / 1 kHz / 10 kHz / 100 kHz
- Basic Accuracy: 0.3% LCR
- Test Signal: 0.5VRMS
- USB Interface Standard
- Light weight Handheld LCR Meter
- Alligator Leads included, SMD tweezers available

1659 Digibridge RLC Meter

- 0.1% Measurement Accuracy
- Cost-Effective Solution
- 4 Test Frequencies 100Hz to 10kHz
- 5 Impedance Parameters
- Built-in Test Fixture

1692 Digibridge RLC Meter

- 0.05% Measurement Accuracy
- 5 Test Frequencies 100Hz to 100kHz
- 5 Impedance Parameters
- Built-in Test Fixture

1900 Series Precision LCR Meters

Common Features

- High Performance, Fast, Production Oriented
- 20 Measurement Parameters
- Basic Accuracy: 0.1% LCR; 0.001 DQ
- DC Resistance Measurements: 0.1mΩ-100kΩ
- 27,000 Test Frequencies: 20Hz to 1MHz
- Programmable Test Voltage: 20mV to 1.0V
- Programmable Source Impedance
- Constant Voltage Mode (Voltage Leveling)
- GPIB, RS232 & Handler Interfaces Standard
- Cable Compensation (1M, 2M, no cable)
- Monitor DUT Voltage & Current
- Storage/Recall of 30 Single tests, 10 Sequential

1910 Inductance Analyzer

- Focused on Inductor Measurements
- DC Bias Current: 1mA to 1A

1920 Precision LCR Meter

- General Purpose
- DC Bias Voltage: 0V to 2.0V, Internal

1689 Digibridge RLC Meter

- The world's standard for AC Resistance, Low Frequency Inductance and Capacitance
- 0.02% Measurement Accuracy
- Programmable Frequency 12 Hz - 100 kHz
- High Speed Measurements up to 50/second
- Widely accepted impedance meter in a metrology environment
- Built-in fixture for testing axial and radial components

1693 Digibridge RLC Meter

- The world's standard for AC Resistance, Low Frequency Inductance and Capacitance
- 0.02% Measurement Accuracy
- Programmable Frequency 12 Hz - 200 kHz
- Extremely Reliable can last up to 30+ years
- 11 Impedance Parameters
- A full, five-digit LED display for RLC; four-digit readout for D and Q
- The US Army's impedance bridge for Metrology

7600 Plus Precision LCR Meter

- R&D and Production Applications
- Wide Frequency Range: 10Hz to 2MHz
- Graphical Sweep and Tabular Display
- 14 Measurement Parameters
- Basic Accuracy: 0.05% LCR; 0.0005 DQ
- Programmable Test Voltage: 20mV to 5.0V
- Programmable Test Voltage: 250uA to 100mA
- Up to 120 measurements/second
- RS232, Handler, and Parallel Printer Standard
- GPIB Optional via 7000-22
- USB Host Port for Storage of Test Setups & Data
- DC Bias Voltage: 2.0V Fixed, Internal
- DC Bias Voltage: 0V to 200V, Requires External DC Power Supply
- AutoAcc (Automatic Accuracy Calculation)

Dedicated Function Test Instruments

In addition to Precision LCR Meters, IET Labs manufactures milliohmmeters, megohmmeters, Inductance, Capacitance and Resistance Standards and Decades. View any product specification at www.ietlabs.com

14 Impedance Terms and Equations*

Parameter	Quantity	Unit Symbol	Formula
Z	Impedance	ohm, Ω	$Z = R_S + jX_S = \frac{1}{Y} = \|Z\| \varepsilon^{j\theta}$
|Z|	Magnitude of Z	ohm, Ω	$\|Z\| = \sqrt{R_S^2 + X_S^2} = \frac{1}{\|Y\|}$
R_S or ESR	Resistance, Real part of Z	ohm, Ω	$R_S = \frac{G_P}{G_P^2 + B_P^2} = \frac{R_P}{1+Q^2}$
X_S	Reactance, Imaginary part of Z	ohm, Ω	$X_S = -\frac{B_P}{G_P^2 + B_P^2}$
Y	Admittance	siemen, S	$Y = G_P + jB_P = \frac{1}{Z} = \|Y\| \varepsilon^{j\phi}$
|Y|	Magnitude of Y	siemen, S (was mho)	$\|Y\| = \sqrt{G_P^2 + B_P^2} = \frac{1}{\|Z\|}$
Gp	Real part of Y	siemen, S	$G_P = \frac{R_S}{R_S^2 + X_S^2}$
Bp	Susceptance	siemen, S	$B_P = -\frac{X_S}{R_S^2 + X_S^2}$
C_S	Series capacitance	farad, F	$C_S = -\frac{1}{\omega X_S} = C_P(1+D^2)$
Cp	Parallel capacitance	farad, F	$C_P = \frac{B}{\omega} = \frac{C_S}{1+D^2}$
L_S	Series inductance	henry, H	$L_S = \frac{X}{\omega} = L_P \frac{Q^2}{1+Q^2}$
Lp	Parallel inductance	henry, H	$L_P = -\frac{1}{\omega B_P} = L_S(1+\frac{1}{Q^2})$
Rp	Parallel resistance	ohm, Ω	$R_P = \frac{1}{G_P} = R_S(1+Q^2)$
Q	Quality factor	none	$Q = -\frac{1}{D} = \frac{X_S}{R_S} = \frac{B_P}{G_P} = \tan\theta$
D or tan δ	Dissipation factor	none	$D = -\frac{1}{Q} = \frac{R_S}{X_S} = \frac{G_P}{B_P} = \tan(90^0 - \theta) = \tan\delta$
θ	Phase angle of Z	degree or radian	$\theta = -\phi$
ϕ	Phase angle of Y	degree or radian	$\phi = -\theta$

NOTES:

1. f = frequency in Hertz; j = square root (-1); $\omega = 2\pi f$
2. R and X are equivalent series quantities unless otherwise defined. G and B are equivalent parallel quantities unless otherwise defined. Parallel R (Rp) is sometimes used but parallel X (Xp) is rarely used and series G (Gs) and series B (Bs) are very rarely used.
3. C and L each have two values, series and parallel. If no subscript is defined, usually series configuration is implied, but not necessarily, especially for C (Cp is common, Lp is less used).
4. Q is positive if it is inductive, negative if it is capacitive. D is positive if it is capacitive. Thus D = -1/Q.
5. Tan d is used by some (especially in Europe) instead of D. tan d = D.

15 NRTLs and Standards Organizations

NRTL stands for Nationally Recognized Testing Laboratories
A2LA American Association for Laboratory Accreditation
http://www.a2la.org/
American National Standards Institute
www.ansi.org
British Standards Institution
www.bsi.org.uk
CENELEC Comité Européen de Normalisation Electrotechnique
www.cenelec.org
Canadian Standards Association
www.csa.ca
IEC International Electrotechnical Commission
www.iec.ch
Institute of Electrical and Electronic Engineers, Inc
www.ieee.org
ISO International Standards Organization
www.iso.org
Japanese Standards Association
www.jsa.jp
National Electrical Manufacturers Association
www.nema.org
NIST National Institute of Standards and Technology
www.nist.gov
OSHA Occupation Safety and Health Administration
www.osha.gov
TÜV Rheinland of North America, Inc.
www.us.tuv.com
Underwriters Laboratories, Inc.
www.ul.com
VDE-Verband Deutscher Elektrotechniker
www.vde.com

16 Helpful Links

TYPE	NAME	ADDRESS	PHONE	WEBSITE
Parts				
874 Connectors And Specialty Cables	Pasternack		949-261-1920	http://www.pasternack.com/
900 Connectors	Maury Microwave	2900 Inland Empire Blvd. Ontario CA 91764	909-987-4715	http://maurymw.com
Equipment				
GenRad ATE Products	Teradyne Inc	321 Harrison Ave. Boston, MA 02118-2238	617-482-2700	http://www.teradyne.com/
GenRad Variacs	IET Labs	534 Main St., Westbury, NY 11590	516-334-5959	http://www.ietlabs.com/
Dielectric Cells	Dielectric Products Co. Gerard Gilkie	178 Orchard St. Watertown, MA 02172	617-924-5688	www.ietlabs.com/dielectric-cells.html
Dielectric Cells	Vertex Image Products Chuck Bobich	RD#1 Box 117 Yukon PA 15698	724-722-3400	http://www.verteximage.com/
Standards				
Inductance, Capacitance & Resistance Standards; Decades, Strobes	IET Labs	534 Main St., Westbury, NY 11590	516-334-5959	http://www.ietlabs.com/
Magazines				
Compliance Engineering				http://www.ce-mag.com/
Conformity	Conformity Magazine			http://www.conformity.com/
EDN Electronic Design News	Reed Business Info. (Formerly Cahners)			http://www.edn.com/
Electronic Products	Hearst Business Publishers			http://www2.electronicproducts.com/
Design West	CMP Media Inc			http://www.ubmdesign.com/
Evaluation Engineering	Nelson Publishing			http://www.evaluationengineering.com

TYPE	NAME	ADDRESS	PHONE	WEBSITE
Passive Component	The Paumanok Group			http://www.passivecomponentmagazine.com/
Test & Measurement World				http://www.tmworld.com/
Resources				
The Capacitor Source	FaradNet			www.faradnet.com
Product Sites				
Electronics	GlobalSpec Inc			http://www.globalspec.com/

17 Typical Measurement Parameters

Component	Type	Frequency	Voltage	Equiv. Circuit	Quantity
Capacitors	Electrolytic, Non-polarized	60 Hz	.1,.3,1	Series	C, D
"	Electrolytic, Polarized	120 Hz	Low, DC bias	Series	C, D
"	Electrolytic, Polarized	100K-1MHz		Series	ESR, |Z|
"	Plastic, Ceramic > 1000pF	1kHz	.1 – 1V AC	Series	C, D
"	Ceramic < 1000pF	1MHz	.1 – 1V AC	Series/ parallel	C, D
Inductors	High-valued	50 - 1000 Hz	varies	Parallel	L, Q, R_P
"	Low-valued (rf)	1k - 1MHz	low	Series	L, Q, R_S
Resistors	Low values	DC - 1kHz	varies	Series	R, Q, L
"	High values	DC - 100Hz	varies	Parallel	R, Q, C_P
Materials	Insulators	DC, 1k, 1M	1, HV DC	Parallel	C, D, R, G, dielectric const, K
"	Semi-conductors	DC, low freq.	varies	Parallel	C, G, C vs. V
"	Conductors	100, 1k	any	Series	R, Q, L
"	Magnetic	50-1 kHz	varies	Series/ parallel	L, Q, R
Motors & Transfor-mers	Capacitance	1k, 1M	1	Parallel	C, D
"	Inductance	50Hz to 1MHz	1	Series	L, Q
"	Resistance	DC, 100Hz	1	Series	R, Q
Cables	Capacitance	1k, 1M	1	Series	C
"	Inductance	as required	any	Series	L
"	Impedance	1k, 1M	any	Series/ parallel	Z
Battery	Impedance	100,1k	1	Series	Z, R
Circuit board	Impedance	1k, 1M	1	Series	C, Z, L, G
Network	Impedance	as required	any	Series/ parallel	R. L, C, Q, G, Z, G, Y, θ

Component	Type	Frequency	Voltage	Equiv. Circuit	Quantity
Filters	Impedance	as required	any	Series/ parallel	R, L, C, Q, G, Z, G, Y, θ
Trans- ducers		as required	any	Series/ parallel	Z, C, L, R, θ
Sensors		as required	any	Series/ parallel	all

18 LCR Selection Guide

Feature	DE-5000	1910 1920	7600 Plus	1692	1689 1689M	1693
Accuracy (±)	0.3% LCR 0.001 DQ 0.18°	0.1% LCR 0.001 DQ 0.18°	0.05% LCR 0.0005 DQ 0.18°	0.05% LCR 0.0003 DQ	0.02% LCR 0.0001 DQ	0.02% LCR 0.0001 DQ
Test Frequency	100, 120, 1k, 10k, 100k	20Hz – 1MHz	10Hz – 2MHz	100, 120, 1k, 10k, 20k, 40k, 50k & 100k Hz	12Hz – 100kHz	12Hz – 200kHz
Test Voltage	0.5V	20mV – 1.0V	20mV – 5.0V	0.3V and 1.0V	5mV – 1.275V	5mV – 1.275V
Test Current	No	No	250uA – 100mA	No	No	Yes Up to 51mA
Monitor V/I DUT	No	Yes	No	No	No	No
Measured Para-meters	L, C, R, D, Q, θ, ESR, DCR	L, C, R, Z, D, Q, θ, Y, G, B, ESR, DCR	L, C, R, Z, D, Q, θ, Y, G, B	L, C, R, D, Q	L, C, R, D, Q	L, C, R, Z, D, Q, θ, Y, G, B
Measure-ment Speed	1.2 sec/meas	Up to 40 meas/sec	Up to 120 meas/sec	Up to 8 meas/sec	Up to 50 meas/sec	Up to 50 meas/sec
Display	5 digit (pri/sec) Δ%, Pass/Fail	Full 5 digit (pri/sec) Eng/Sci Δ, Δ%, Pass/Fail Blank (No display)	Full 7 digit (pri/sec), Bin #, Bin Sum, Δ, Δ%, Pass/Fail Blank (No display)	Full 5 + 4 digits Bin #, Δ, Δ%	Full 5 + 4 digits Bin #, Δ, Δ%	Full 5 + 4 digits Bin #, Δ, Δ%
Plot: F, V, I	No	No	Yes	No	No	No
Sequence	No	Yes	Yes	No	No	No
DC Bias Voltage	No	1920 Only 0 - 2V INT	2V Fixed INT 0 - 200V EXT	No	2V INT 0 - 60V EXT	2V INT 0 - 60V EXT
DC Bias Current	No	1910 Only 0 – 1.0A INT 0 – 20.0A	No	No	No	No
Test Connection	4-banana socket Kelvin plus	4-BNC Kelvin plus Optional	4-BNC Kelvin plus Optional	Built-in Radial/Axial	1689 Built-in Radial/Axial	4-BNC Optional fixtures

Feature	DE-5000	1910 1920	7600 Plus	1692	1689 1689M	1693
	Optional fixtures	fixtures	fixtures	Optional fixtures	1689M 4-BNC Optional fixtures	
Auto Para-meters	Yes	Yes	Option	No	No	Yes
Auto Range	Yes	Yes	Yes	Yes	Yes	Yes
Binning	No	Yes	Yes (15)	Yes (8)	Yes (15)	Yes (15)
Bin Sum	No	No	Yes	Yes	Yes	Yes
Averaging	Yes (1 – 1000)	Yes (1 – 1000)	Yes (1 – 1000)	No	Yes (1-256)	Yes (1-256)
Median Mode	No	Yes	Yes	No	Yes	Yes
Offset / Zero	Yes	Yes	Yes	Yes	Yes	Yes
Calibration	Built-In Auto Cal	Built-In Auto Cal	Built-In Auto Cal	Built-In Auto Cal	Built-In Auto Cal	Built-In Auto Cal
Save Setup	Yes	Yes	Yes	Yes	Yes	Yes
USB	Yes	No	Yes Host Port	No	No	No
RS232	No	Yes	Yes	Yes	No	No
IEEE-488	No	Yes	Option	Option	Option	Option
Handler Port	No	Yes	Yes	Option	No	No
Printer Port	No	No	Yes	No	No	No
Constant V	No	Yes	No	Yes	Yes	Yes
Constant I	No	No	Yes	No	No	Yes
Source Impedance (Ω)	na	5, 25, 50, 100Ω Selectable	25, 400, 6.4k, 100kΩ (Range dependent)	25, 400, 6.4k, 100kΩ (Range dependent)	25, 400, 6.4k, 100kΩ (Range dependent)	25, 400, 6.4k, 100kΩ (Range dependent)
Delta % (Δ %)	Yes	Yes	Yes	Yes	Yes	Yes
Delta LCR	Yes	Yes	Yes	Yes	Yes	Yes
D & Q in ppm	Yes	Yes	Yes	No	Yes	Yes
Ratio Display	No	No	No	No	Yes	Yes
Program Delay	Yes 0-10s	Yes 0-10s	Yes 0-10s	No	Yes 0 – 99999ms	Yes 0 – 99999ms
Battery Operation	Yes	No	No	No	No	No

19 LCR Accessory Selection Guide

Accessory Part #	Description	DE 5000	1910 1920	7600 Plus	1692 1659 1689	1693 1689M
1689-9600	Remote Component Test Fixture		x	x	!	x
1689-9605	Remote Component Test Fixture with Go/No Go LEDs				!	x
1900-WZD	1900 Virtual Front Panel		x			
7600-WZD	7600 Series Front Panel			x		
DE-5000-DKT	Data Kit for USB	x				
630158	RS232 Cable 9pin to 9pin		x	x		
1689-9602	BNC Cable Set (1 meter)		x	x	!	x
1689-9602-2	BNC Cable Set (2 meters)		x	x	!	x
1689-9601	BNC Adapter Box				x	
1700-03	Kelvin Clip Leads		x	x	!	x
2000-16	Rack Mount Flanges 1900		x			
1689-9611	Rack Mount Kit for 1689M/1693					x
7000-00	Rack Mount Kit 7000			x		
7000-04	Alligator Clip/banana Leads		x	x	!	x
1657-9600	Banana Plug Extender Cable				x	
7000-05	Chip Component Tweezers		x	x	!	x
7000-07	Chip Component Test Fixture		x	x	!	x
7000-09	Calibration Kit for 7000			x		
7000-22	IEEE Option for 7600 Plus			x		
900032	Calibration Kit for 1900		x			
1689-9406	Calibration Kit for Digibridge				x	x
1689-9640	IEEE Digibridge Interface				x	x
	! requires 1689-9601 for use					

20 IET Labs Application Notes

IET Labs has an extensive library of application notes and GenRad Experimenters.
See www.ietlabs.com for latest application notes.

21 Glossary

AC	Alternating current, an electric current that has one polarity during half of the cycle and the opposing polarity during the other half of the cycle. Residential electricity is AC.
Accuracy	The difference between the measured value or reading and the true or accepted value. The accuracy of an LCR meter is typically given as a ± percentage of the measured value for primary parameters and ± an absolute value for the secondary parameter. Example: ± 0.05% for L, C & R and ± 0.0005 for D.
ANSI	American National Standards Institute, an industry association that defines standards for data processing and communication.
Basic Accuracy	Basic accuracy is specified at optimum test signal, frequency, highest accuracy setting or slowest measurement speed, and the impedance of the DUT. As a general rule this means 1VAC RMS signal level, 1kHz frequency, high accuracy (1 measurement/second), and a DUT impedance between 10Ω and 100kΩ.
Binning	A procedure for sorting components into bins using sequential limits or nested limits.
Breakdown	Failure of electrical insulation to provide a dielectric barrier to current flow.
Capacitor	A passive component comprised of two conductors separated by a dielectric. A capacitor stores charge, blocks DC flow and allows AC flow at a specified range of frequencies.
Capacitance (C)	The ratio of charge on either plate of a capacitor to the potential difference (voltage) across the plates. When a voltage is applied, current flows immediately at a high rate and then decays exponentially toward zero as the charge builds up. If an AC voltage is applied, an AC current appears to flow continuously because the polarity of the voltage is reversed at the frequency of the applied voltage. The waveform of this current, however, is displaced in time from the applied voltage by 90°.
Capacitive Reactance (Xc)	Measurement of the actual AC resistance of a capacitor. How effective a capacitor is in allowing AC to flows depends upon its capacitance and frequency. $X_c = 1/2\pi fC$.

Clearance	The shortest distance between two conductors through air or insulating medium.
Compare	A procedure for sorting components by comparing the component's measured value against a known standard.
Creepage	Creepage is the shortest path along the surface of an insulator or insulating medium that separates two conductors. The insulator or insulation medium cannot be air.
CSA	Canadian Standards Association.
Current Draw	The mains current consumed by the product or DUT.
DC	Direct current, non-reversing polarity. The movement of charge is in one direction. Used to describe both current and voltage. Batteries supply direct current.
Delay Time	The period during which an instrument waits to do a task.
Dielectric	An insulating material in which an electric field can be sustained with a minimum dissipation of power.
Dielectric Constant (K)	Ratio of the capacitance of a capacitor filled with a given dielectric to that same capacitor having only a vacuum as a dielectric.
Discharge	The act of draining off an electrical charge to ground. Devices that retain charge should be discharged after a DC hipot or IR test.
Dissipation Factor (D)	Synonym for loss tangent; a quantification of the loss in the capacitor Capacitance and dissipation factor for devices greater than 1000pF are tested at 1 KHz; devices of lower value are tested at 1 MHz. The testing of capacitors conforms to the guidance of military and industry standards
DUT	Device Under Test - the product being tested.
Dwell Time	The amount of time the DUT is allowed to stabilize at the test voltage before measurements are performed.
Electric Current (I)	The flow of electrons (or electron "holes") through a conducting material, which may be a solid, liquid, or gas; the rate of flow of charge past a given point in an electric circuit. The magnitude of current flow through the conductor is proportional to the magnitude of voltage or electrical potential applied across the conductor and inversely proportional to the resistance (or impedance) of the conductor. Current is expressed in amperes or milliamperes (amperes/1000).
Equivalent Circuit	The configuration of the device under test. The components of the DUT can be represented as a series or parallel equivalent circuit.
Fall Time	The amount of time it takes to gradually decrease the voltage to zero potential.

Frequency (f)	The rate at which a current or voltage reverses polarity and then back again completing a full cycle, measured in Hertz (Hz) or cycles per second.
GFCI	Ground Fault Circuit Interrupter, a safety device that breaks a power circuit as soon as it detects current flow of a certain magnitude through the ground return of a power circuit. Also known as GFI.
Ground	The base reference from which voltages are measured, nominally the same potential as the earth. Also the side of a circuit that is at the same potential as the base reference.
Handler	Device for remote control of test instrument in component handling operations.
Hertz (Hz)	The unit of measure of frequency, equivalent to cycles per second.
High Limit	The upper value for a test to be considered a PASS. If the measured value is higher than the high limit the test is considered a FAIL. In hipot, leakage current and ground bond tests a high limit is required.
IEEE	Institute of Electrical and Electronic Engineers.
IEEE 488	General Purpose Interface Bus (GPIB) - an industry standard definition of a parallel bus connection for the purpose of communicating data between devices.
Impedance (Z)	A vector summation of resistance (R) and reactance (X). A term used with alternating current circuits to describe the "AC resistance" to the flow of current through a circuit when an AC voltage is applied across the terminals of that circuit. Impedance is a complex quantity composed of real (in phase with voltage) and reactive (out of phase by 90°) components. Impedance is calculated as voltage divided by current. Capacitors: Reactance = $X_C = 1/j\omega C$ Inductors: Reactance = $X_L = j\omega L$ Resistors: Resistance = R $Z = \sqrt{X^2 + R^2}$
Inductor	L (as in LCR). An inductor is a coil of wire. It is used to create electromagnetic induction in a circuit.
Inductance (L)	The property of a coil to oppose any change in current through it. If the turns (coils) of the wire are stretched out, the intensity of the magnetic field will diminish and the inductance will be less. Unit of measure is the Henry (H).
Inductive Reactance	A measure of how much the electro-magnetic force (emf) of a coil will oppose current variation through the coil. The amount of reactance is directly proportional to the current variation: $X_L = 2\pi fL$.

Insulation	The protection against unwanted flow of current through a path, as between a circuit of a product and the ground reference. Materials that prevent current flow are referred to as insulators or dielectrics.
Kelvin Connection	A circuit connection that automatically compensates for measurement errors caused by resistance of leads between a tester and the point of measurement on a DUT.
Level	The test signal level is the programmed RMS voltage of the generator in an LCR meter. The actual test voltage across the DUT is always less than the programmed level.
Load	The total resistance or impedance of all circuits and devices connected to a voltage source.
Low Limit	The lower value for a test to be considered a PASS. If the measured value is lower than the low limit the test is considered a FAIL.
Megohmmeter	An instrument designed to measure high values of resistance using a DC voltage usually greater than 50 V DC.
Milliohmmeter	An instrument designed to measure low values of resistance using a DC current or voltage.
NIST	National Institute of Standards and Technology, an agency of the U.S. Government that sets standards for physical measurements and references, formerly called the National Bureau of Standards.
NRTL	Nationally Recognized Testing Laboratory, such as Underwriters Laboratories (UL), Factory Mutual (FM), or Canadian Standards Association (CSA).

Offset	An automatic zeroing function to correct for leakage currents or additional resistance due to test leads or fixtures. An offset is performed by making a measurement at the programmed test settings, calculating the difference between the leakage current or resistance measured and the ideal current or resistance and then subtracting this difference from all future measurements.
Ohm's Law	The fundamental law of electrical circuits that describes the relationship between voltage, current and impedance (or resistance). For DC circuits, Ohm's Law states that Current =Voltage/Resistance (I=V/R). For AC circuits, Current = Voltage/Impedance (also I=V/R). Stated conversely, Voltage = Current x Resistance (DC) or Voltage = Current x Impedance (AC). The difference between the DC resistance and AC impedance is that AC circuits must deal with phase relationships and DC circuits do not.
Ohm (Ω)	The unit of measurement of resistance and impedance, derived from Ohm's Law.
OSHA	Occupational Safety and Hazards Administration, an agency of the U.S. Government that regulates industrial safety.
Parameter	Electrical property being tested. The primary parameter (L, C, R) is the first property characteristic of the device under test. The secondary parameter (D, Q, q) is the second property characteristic of the device under test.
Permittivity (ε)	The dielectric constant multiplied by the dielectric constant of empty space (ε_o), where the permittivity of empty space is a constant in Coulomb's law, equal to a value of 1 in centimeter-gram-second units and to 8.854 x 10-12 farads/meter in rationalized meter-kilogram-second units.
Phase	The time relationships between alternating voltages, currents, and impedances. Usually expressed as complex vectors with "real" (in-phase) and "reactive" (out of phase) components.
Polarization	A term used to describe a "one way" limitation on the insertion of a plug into a receptacle for a corded product. A polarized plug can be inserted in only one orientation and cannot be reversed.
Potential	Electrical potential is a term equivalent to "voltage".
Prefixes	The prefixes for Multiple Scientific Engineering Symbols are:

1000000000000000 1015 Peta P
1000000000000 1012 Tera T
1000000000 109 Giga G
1000000 106 Mega M
1000 103 Kilo k
0.001 10-3 milli m

0.000001	10-6	micro	m
0.000000001	10-9	nano	n
0.000000000001	10-12	pico	p
0.000000000000001	10-15	femto	f

Protective Earth	Conductor that connects between any protectively earthed parts of a Class I product and an external protective earth connection.
Microsecond	One millionth of a second.
Q (Quality Factor)	The ratio between the energy stored in a circuit (in C and L) and the energy dissipated (by R):
Range	The resistance ranges the test instrument uses for reference in making the measurement.
Reactive	The component of an AC voltage, current, or impedance that is 90° out of phase with the "real" or in phase component. Reactive components are associated with capacitive or inductive circuits.
Real	The component of a voltage, current, or impedance that is in phase with the "real" component. Real components are associated with purely resistive circuits.
Regulation	When applied to electrical circuits, regulation refers to the variation in output voltage that occurs when the input voltage changes or when the connected load changes. When applied to test laboratories and agencies, refers to the control exercised by these entities over test specs and rules.
Repeatability	The difference between successive measurements with no changes in the test setup or test conditions.
Reproducibility	Similar to repeatability but adds the element of what could be expected under real life conditions. Reproducibility would take into account the variability in things like fixtures, where the DUT being tested is removed from the fixture and re-inserted.
Resolution	The smallest value that can be shown on the display in a digital instrument. LCR meters typically specify a measurement range that is the largest and smallest value that can be shown on that meter's display.
Resistance (R)	The electrical characteristic that impedes the flow of current through a circuit to which voltage has been applied. Resistance is calculated by Ohm's Law as voltage divided by current (for DC circuits). For AC circuits, it is the in-phase or "real" component of impedance. Units are expressed in ohms (Ω).
RS232	An industry standard definition for a serial line communication link or port.
Scanner	A scanner is a device designed to switch or matrix signals.
SCC	Standards Council of Canada, an agency of the Canadian Government analogous to OSHA in the United States.

Speed	The rate per second at which the instrument makes a measurement. Speed is inversely proportional to accuracy.
Spike	A large momentary deviation from a normal voltage or current waveform.
Stabilization Time	The time required for a transient disturbance to decay to a steady state value.
Source Impedance	The impedance of the measuring instrument applied to the input terminals of the device under test (DUT). If 1V is the programmed voltage and the source impedance is 25 Ω and the DUT is 25 Ω, then the voltage at the DUT is 0.5V.
Trigger	The device for initiating the test (applying the voltage or current).
External Trigger	The test is initiated via an external source such as a computer with an IEEE-488 or Handler interface. One measurement is made each time the external trigger is asserted.
Internal Trigger	The instrument continuously makes measurements.
Manual Trigger	The operator initiates the test by pressing the [START] button. One measurement is made each time the trigger is pressed.
UL	Underwriters Laboratories, Inc., an NRTL located in Illinois.
Voltage (V)	The electrical potential applied to a circuit.
Waveform	The instantaneous value of a variable such as voltage or current plotted against time.
X (Reactance)	Reactance is the imaginary component of Impedance.
Y (Admittance)	Admittance is the reciprocal of Impedance. $Y = 1/Z$
Z (Impedance)	Impedance is the sum of alternating current oppositions (capacitive reactance, inductive reactance, and resistance). $Z = R + jX$

Research for this primer found in:
"Faraday, Michael", "Marconi, Guglielmo, Marchese", "Radio", and "Electronics" Microsoft® Encarta® Online Encyclopedia 2001, http://www.encarta.msn.com
"A History of the General Radio Company", Arthur E. Thiessen, 1965©
"The Automatic Capacitance Bridge", The General Radio Experimenter, General Radio Company 1965©
"Automatic Capacitor-Testing Systems" The General Radio Experimenter, General Radio Company 1966©
"Company History & TimeLine", http://www.genrad.com/corp_info, March 2001