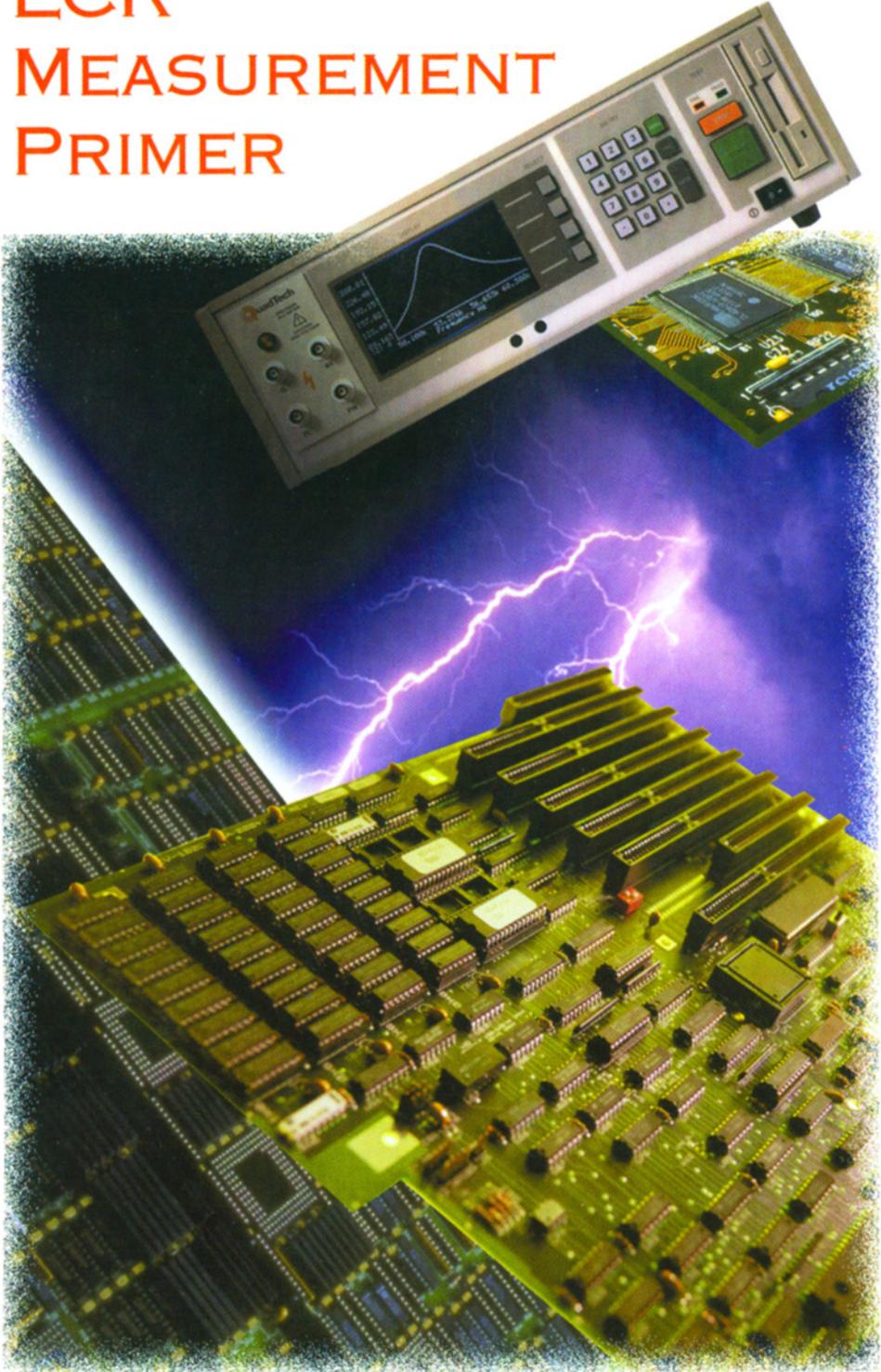


# LCR MEASUREMENT PRIMER



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# Preface

The intent of this reference primer is to explain the basic definitions and measurement of impedance parameters, also known as LCR. This primer provides a general overview of the impedance characteristics of an AC circuit, mathematical equations, connection methods to the device under test and methods used by measuring instruments to precisely characterize impedance. Inductance, capacitance and resistance measuring techniques associated with passive component testing are presented as well.

LCR Measurement Primer  
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# Impedance

## Impedance

Impedance is the basic electrical parameter used to characterize electronic circuits, components, and materials. It is defined as the ratio of the voltage applied to the device and the resulting current through it. To put this another way, impedance is the total opposition a circuit offers to the flow of an alternating current (ac) at a given frequency, and is generally represented as a complex quantity, which can be shown graphically. The basic elements that make up electrical impedances are inductance, capacitance and resistance: L, C, and R, respectively.

In the real world electronic components are not pure resistors, inductors or capacitors, but a combination of all three. Today's generation of LCR meters are capable of displaying these parameters and can easily calculate and display many other parameters such as Z, Y, X, G, B, D, etc. This primer is intended as an aid in understanding which ac impedance measurements are typically used and other factors that need to be considered to obtain accurate and meaningful impedance measurements.

## Definitions

The mathematical definition of resistance for dc (constant voltage) is the ratio of applied voltage V to resulting current I. This is Ohms Law:  $R = V/I$ . An alternating or ac voltage is one that regularly reverses its direction or polarity. If an ac voltage is applied to a circuit containing only resistance, the circuit resistance is determined from Ohms Law.

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

## Complex Quantity

However, if capacitance or inductance are present, they also affect the flow of current. The capacitance or inductance cause the voltage and current to be out of phase. Therefore, Ohms law must be modified by substituting impedance (Z) for resistance. Thus for ac, Ohm's Law becomes :  $Z = V/I$ . Z is a complex number:  $Z = R + jX$ . A complex number or quantity has a real component (R) and an imaginary component (jX).

## Phase Shift

The phase shift can be drawn in a vector diagram which shows the impedance Z, its real part  $R_s$ , its imaginary part  $jX_s$  (reactance), and the phase angle  $\theta$ . Because series impedances add, an equivalent circuit for an impedance would put  $R_s$  and  $X_s$  in series hence subscript 's'. The reciprocal of Z is Admittance, Y which is also a complex number having a real part  $G_p$  (conductance) and an imaginary part  $jB_p$  (susceptance) with a phase angle  $\phi$ . Note  $\theta = -\phi$ . Because admittances in parallel add, an equivalent circuit for an admittance would put  $G_p$  and  $B_p$  in parallel. Note from the formulas below that, in general,  $G_p$  does not equal  $(1/R_s)$  and  $B_p$  does not equal  $-(1/X_s)$ .

Refer to Table 1 for Impedance terms, units of measure and equations.

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

**Table 1: Impedance Terms & Equations**

Parameter	Quantity	Unit Symbol	Formula
Z	Impedance	ohm, $\Omega$	$Z = R_s + jX_s = \frac{1}{Y} =  Z  e^{j\mathbf{q}}$
Z	Magnitude of Z	ohm, $\Omega$	$ Z  = \sqrt{R_s^2 + X_s^2} = \frac{1}{ Y }$
R <sub>S</sub> or ESR	Resistance, Real part of Z	ohm, $\Omega$	$R_s = \frac{G_p}{G_p^2 + B_p^2} = \frac{R_p}{1 + Q^2}$
X <sub>S</sub>	Reactance, Imaginary part of Z	ohm, $\Omega$	$X_s = -\frac{B_p}{G_p^2 + B_p^2}$
Y	Admittance	siemen, S	$Y = G_p + jB_p = \frac{1}{Z} =  Y  e^{j\mathbf{f}}$
Y	Magnitude of Y	siemen, S (was mho)	$ Y  = \sqrt{G_p^2 + B_p^2} = \frac{1}{ Z }$
G <sub>p</sub>	Real part of Y	siemen, S	$G_p = \frac{R_s}{R_s^2 + X_s^2}$
B <sub>p</sub>	Susceptance	siemen, S	$B_p = -\frac{X_s}{R_s^2 + X_s^2}$
C <sub>S</sub>	Series capacitance	farad, F	$C_s = -\frac{1}{\omega X_s} = C_p(1 + D^2)$
C <sub>p</sub>	Parallel capacitance	farad, F	$C_p = \frac{B}{\omega} = \frac{C_s}{1 + D^2}$
L <sub>S</sub>	Series inductance	henry, H	$L_s = \frac{X}{\omega} = L_p \frac{Q^2}{1 + Q^2}$
L <sub>p</sub>	Parallel inductance	henry, H	$L_p = -\frac{1}{\omega B_p} = L_s(1 + \frac{1}{Q^2})$
R <sub>p</sub>	Parallel resistance	ohm, $\Omega$	$R_p = \frac{1}{G_p} = R_s(1 + Q^2)$
Q	Quality factor	none	$Q = -\frac{1}{D} = \frac{X_s}{R_s} = \frac{B_p}{G_p} = \tan \mathbf{q}$
D, DF or tan $\delta$	Dissipation factor	none	$D = -\frac{1}{Q} = \frac{R_s}{X_s} = \frac{G_p}{B_p} = \tan(90^\circ - \mathbf{q}) = \tan \mathbf{d}$
$\theta$	Phase angle of Z	degree orradian	$\mathbf{q} = -\mathbf{f}$
$\phi$	Phase angle of Y	degree or radian	$\mathbf{f} = -\mathbf{q}$

**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 (R<sub>p</sub>) is sometimes used but parallel X (X<sub>p</sub>) is rarely used and series G (G<sub>s</sub>) and series B (B<sub>s</sub>) 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 (C<sub>p</sub> is common, L<sub>p</sub> 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  $\delta$  is used by some (especially in Europe) instead of D.  $\tan \delta = D$ .

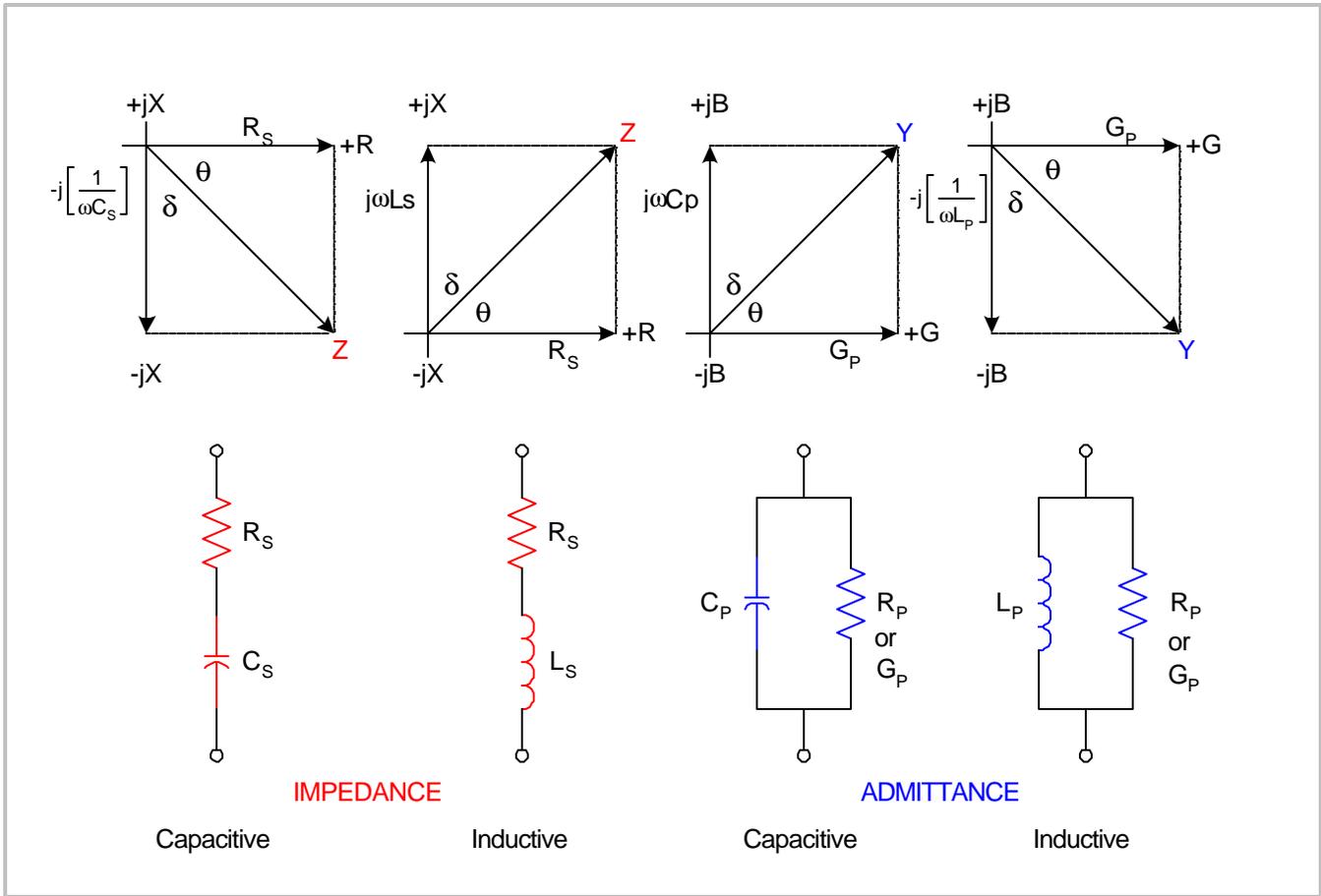


Figure 1: Phase Diagrams

### Series and Parallel

At any specific frequency an impedance may be represented by either a series or a parallel combination of an ideal resistive element and an ideal reactive element which is either capacitive or inductive. Such a representation is called an equivalent circuit and illustrated in Figure 1.

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.

Since the impedance of two devices in series is the sum of their separate impedances, we can think of an impedance as being the series combination of an ideal resistor and an ideal capac-

itor or inductor. This is the series equivalent circuit of an impedance comprising an equivalent series resistance and an equivalent series capacitance or inductance (refer to Figure 1). Using the subscript s for series, we have equation 1:

$$1: Z = R_s + jX_s = R_s + j\omega L = R_s - \frac{j}{\omega C}$$

For a complicated network having many components, it is obvious that the element values of the equivalent circuit will change as the frequency is changed. This is also true of the values of both the elements of the equivalent circuit of a single, actual component, although the changes may be very small.

Admittance,  $Y$ , is the reciprocal of impedance as shown in equation 2:

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

It too is complex, having a real part, the ac conductance  $G$ , and an imaginary part, the susceptance  $B$ . Because the admittances of parallel elements are additive,  $Y$  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 (refer to Figure 1). Using the subscript  $p$  for parallel elements, we have equation 3:

$$3: Y = G_p + jB_p = G_p + j\omega C_p = G_p - \frac{j}{\omega L}$$

Note that an inductance susceptance is negative and also note the similarity or duality of this last equation and Equation 1.

It is important to recognize that, in general,  $G_p$  is not equal to  $1/R_s$  and  $B_p$  is not equal to  $1/X_s$  (or  $-1/X_s$ ) as one can see from the calculation in equation 4.

$$\begin{aligned} 4: Y &= \frac{1}{Z} = \frac{1}{R_s + jX_s} \\ &= \left[ \frac{R_s}{R_s^2 + X_s^2} - \left( j \frac{X_s}{R_s^2 + X_s^2} \right) \right] \\ &= G_p + jB_p \end{aligned}$$

Thus  $G_p = 1/R_s$  only if  $X_s = 0$ , which is the case only if the impedance is a pure resistance, and  $B_p = -1/X_s$  (note the minus sign) only if  $R_s = 0$ , that is, the impedance is a pure capacitance or inductance.

$G_p$ ,  $C_p$  and  $L_p$  are the equivalent parallel parameters. Since a pure resistance is the reciprocal of a pure conductance and has the same symbol, we can use  $R_p$  instead of  $G_p$  for the resistor symbols in Figure 1, noting that  $R_p = 1/G_p$  and  $R_p$  is the equivalent parallel resistance. (By analogy, the reciprocal of the series resistance,  $R_s$ , is series conductance,  $G_s$ , but this quantity is rarely used).

Two other quantities,  $D$  and  $Q$ , are useful, not only to simplify the conversion formulas of Table 1, but also by themselves, as 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.

$$5: D = \frac{R_s}{X_s} = \frac{G_p}{B_p} = \frac{1}{Q}$$

A low  $D$  value, or high  $Q$ , means that a capacitor or inductor is quite pure, while a low  $Q$ , or high  $D$ , means that a resistor is nearly pure. In Europe, the symbol used to represent the dissipation factor of a component is the tangent of the angle delta, or  $\tan \delta$ . Refer to Table 1.

Some conventions are necessary as to the signs of  $D$  or  $Q$ . For capacitors and inductors,  $D$  and  $Q$  are considered to be positive as long as the real part of  $Z$  or  $Y$  is positive, as it will be for passive components. (Note, however, that transfer impedance of passive networks can exhibit negative real parts). For resistors, a common convention is to consider  $Q$  to be positive if the component is inductive (having a positive reactance), and to be negative if it is capacitive (having a negative reactance).

Formulas for D and Q in terms of the series and parallel parameters are given in Table 1. Note that the D or Q of an impedance is independent of the configuration of the equivalent circuit used to represent it.

It should be emphasized that these series and parallel equivalent circuits both have the same value of complex impedance at a single frequency, but at any other frequency their impedances will be different. An example is illustrated in Figure 2.

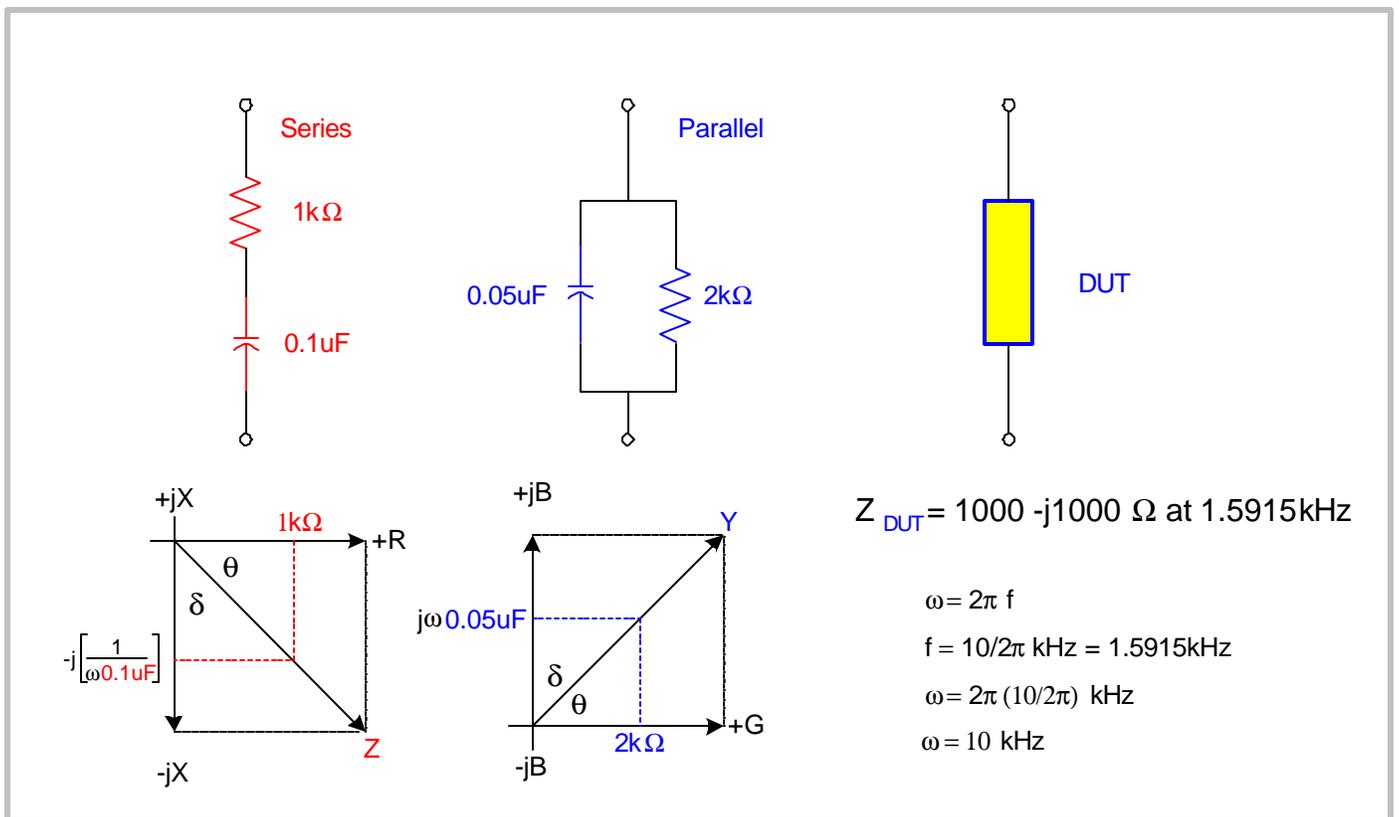


Figure 2: Complex Impedance

# Connection Methods

Connection to the device under test (DUT) is crucial in determining the most accurate value of the DUT's impedance. 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. Refer to QuadTech application note 035027 for an excellent tutorial on Multi-Terminal Impedance Measurements. For the discussion in this primer we will illustrate 2, 3 and 4-terminal connection methods. Note: 1-terminal = 1 wire = 1 lead = 1 connection.

## Two-Terminal Measurements

The impedance of a device is defined by Ohm's Law as the ratio of the voltage across it to the current through it. This requires at least two connections and therefore the arithmetic of terminals starts with two. With only two terminals, the same terminals must be used for both applying a current and measuring a voltage as illustrated in Figure 3.

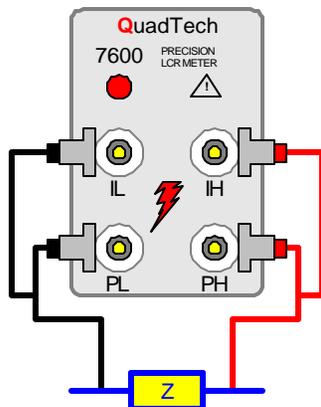


Figure 3: Two Terminal Measurement

When a device is measured in this way it might not be an accurate measurement. There are two types of errors and these are the errors that measurements with more connections will avoid, one is the lead inductance and lead resistance in series with the device and the other is stray capacitance between the two leads, both of which affect the measurement results. Because of these error sources, the

typical impedance measurement range for a two-terminal connection is limited to  $100\Omega$  to  $10k\Omega$ .

## 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  $1\Omega$  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.

This circuitry associated Lord Kelvin's name so closely with the four-terminal connection technique that "Kelvin" is commonly used to describe this connection.

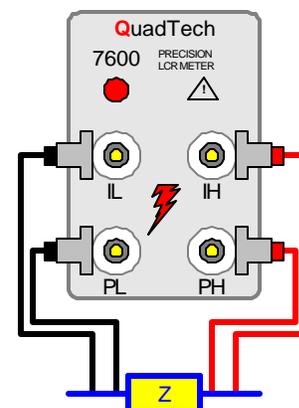


Figure 4: Four Terminal

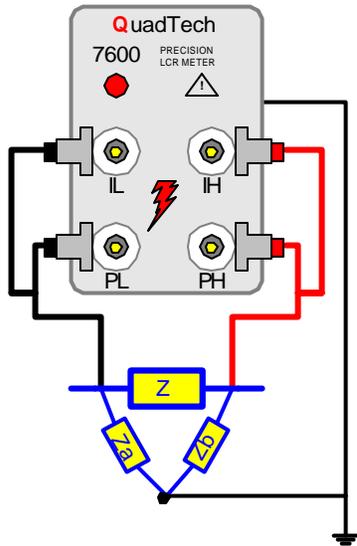


Figure 5: 7600 3-Terminal Kelvin

### 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  $Z_x$ ) can be removed by intercepting it with a shield tied to the guard point. Likewise, "shunting  $Z_x$ " 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 measure-

ments are simply called guarded measurements. They are also called direct impedance measurements. Figure 6 illustrates one representation of a passive 3-terminal network.

The impedance  $Z_x$  is that impedance directly between points A and B. As shown by equation 6, errors caused by  $Z_a$  and  $Z_b$  have been changed. If it were not for the series impedances, the effect of  $Z_a$  and  $Z_b$  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 ( $z_1/Z_a$  and  $z_3/Z_b$ ) the "series/shunt" error. It's caused by a voltage, or current, divider effect. The voltage between point A and guard is reduced because the attenuating or dividing effect of the impedances  $z_1$  and  $Z_a$ . Likewise,  $Z_b$  and  $z_3$  divide the current  $I_x$  so that it doesn't all flow in the ammeter. Note that this error is a constant percent error, independent of the value of  $Z_x$ . 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.

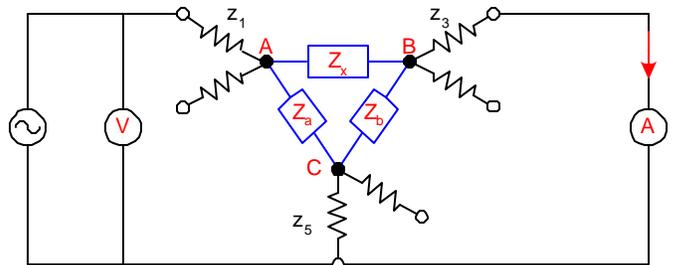
Figure 6:

### Three-Terminal Guarded using Delta Impedance Configuration

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

Equation 6:  
formula for Figure 6

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



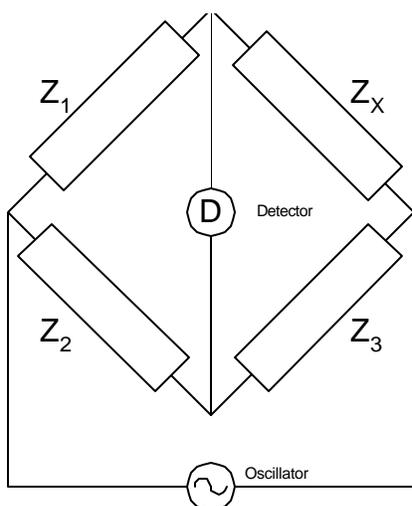
# Impedance Measuring Instruments

Digital LCR meters rely on a measurement process of measuring the current flowing through the device under test (DUT), the voltage 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.

## Methods

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

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



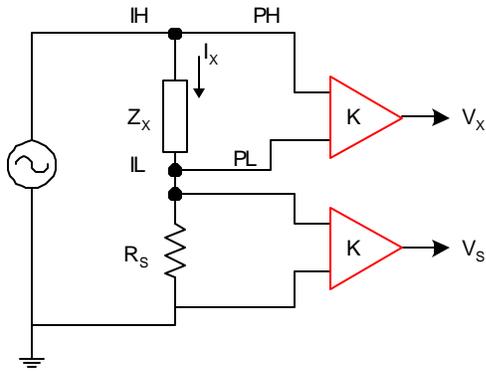
**Figure 7: Bridge Method**

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 QuadTech 7000 LCR Meter uses a principle of measurement which differs significantly from that employed by the traditional measuring instruments. In particular, the 7000 uses digital techniques for signal generation and detection. In the elementary measurement circuit as shown in Figure 8, both the voltage across the device under test ( $Z_x$ ) and the voltage across a reference resistor ( $R_s$ ) are measured, which essentially carry the same current.

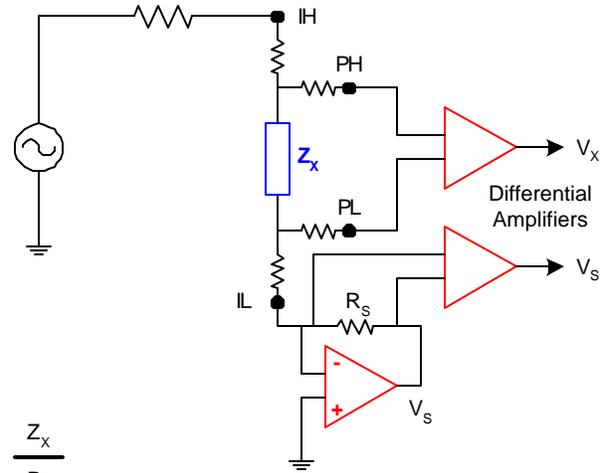
The voltage across  $Z_x$  is  $V_x$  and the voltage across  $R_s$  is  $V_s$ . Both voltages are simultaneously sampled many times per cycle of the applied sine wave excitation. In the case of the 7000, there are four reference resistors. The one used for a particular measurement is the optimal resistor for the device under test, frequency, and amplitude of the applied ac signal. For both  $V_x$  and  $V_s$  a real and imaginary (in phase and quadrature) component are computed mathematically from the individual sample measurements.

The real and imaginary components of  $V_x$  and  $V_s$  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  $V_x$  ( $V_{xr}$  and  $V_{xi}$ ) are combined with the real and imaginary components of  $V_s$  ( $V_{sr}$  and  $V_{si}$ ) and the known characteristics of the reference resistor to determine the apparent impedance of the complex impedance of  $Z_x$  using complex arithmetic.



$$Z_x = \frac{V_x(R_s)}{V_s}$$

7000 Measurement Circuit, Simplified



$$\frac{V_x}{V_s} \approx \frac{Z_x}{R_s}$$

7000 Measurement Circuit, Active 5-Terminal

**Figure 8: 7000 Measurement Circuit**



**Figure 9: QuadTech 7600 LCR Meter**

## 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.

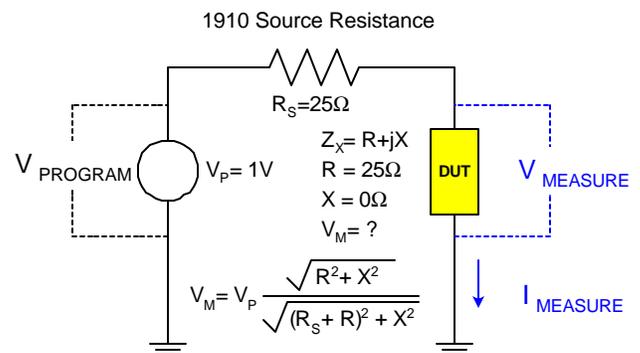
## Test Voltage

The ac output of most LCR meters can be programmed to select the signal level applied to the DUT. Generally, the programmed level is obtained under an open circuit condition.

A source resistance ( $R_s$ , 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 ( $R_s$ ) and the impedance value of the device.

Figure 10 illustrates the factors of constant source impedance, where the programmed voltage is 1V but the voltage to the test device is 0.5V.

Some LCR meters, such as the QuadTech 1900 have a voltage leveling function, where the voltage to the device is monitored and maintained at the programmed level.



**Figure 10: Source Impedance Factors**

## 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.

Range holding, rather than autoranging, is a feature sometimes used in specific applications. For example, when repetitive testing of similar value components, range holding can reduce test time. Another use of range hold occurs when measuring components whose value falls within the overlap area of two adjacent ranges, where if allowed to autorange the instrument's display can sometimes change resulting in operator confusion.

## Integration Time

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 improve repeatability, try the measurement averaging function. In averaging mode multiple measurements are made and the average of these is calculated for the end result. All of this is a way of reducing unwanted signals and effects of unwanted noise, but does require a sacrifice of time.

## Median Mode

A further improvement of repeatability can be obtained by employing the median mode func-

tion. In median mode 3 measurements are made and two thrown away (the lowest and the highest value). 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

Many testers today must be equipped with some type of standard data communication interface for connection to 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.



Figure 11: 7000 Series Computer Application

# Test Fixtures and Cables

Test fixtures (fixturing) and cables are vital components of your test setup and in turn play an important role in the accuracy of your impedance measurements. Consider these factors pertaining to test fixtures and cables.

## Compensation

Compensation reduces the effects from error sources existing between the device under test and the calibrated connection to the measuring instrument. The calibrated connection is determined by the instrument manufacturer, which can be front or rear panel connections, or at the end of a predefined length of cable. Compensation will ensure the best measurement accuracy possible on a device at the selected test conditions. When a measurement is affected by a single residual component the compensation is simple.

Take the case of stray lead capacitance ( $C_{STRAY}$ ) in parallel with the DUT capacitance ( $C_X$ ), illustrated in Figure 12. The value of the stray capacitance can be measured directly with no device connected. When the device is connected the actual DUT value can be determined by subtracting the stray capacitance ( $C_{STRAY}$ ) from the measured value ( $C_{MEASURE}$ ). The only problem is, its not always this simple when stray residuals are more than a single component.

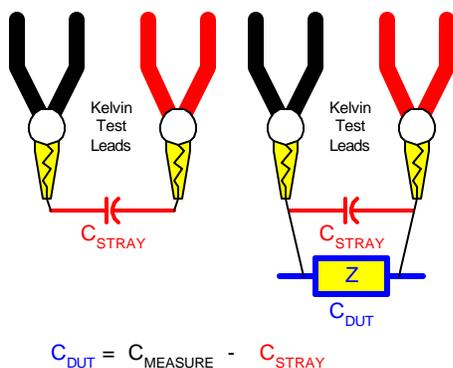


Figure 12: Lead Compensation

## Open/Short

Open/Short correction is the most popular compensation technique used in most LCR instruments today. When the unknown terminals are open the stray admittance ( $Y_{open}$ ) is measured. When the unknown terminals are shorted the residual impedance ( $Z_{short}$ ) is measured. When the device is measured, these two residuals are used to calculate the actual impedance of the device under test.

When performing an OPEN measurement it is important to keep the distance between the unknown terminal the same as they are when attached to the device. It's equally important to make sure that one doesn't touch or move their hands near the terminals. When performing a SHORT measurement a shorting device (shorting bar or highly conductive wire) is connected between the terminals. For very low impedance measurements it is best to connect the unknown terminals directly together.

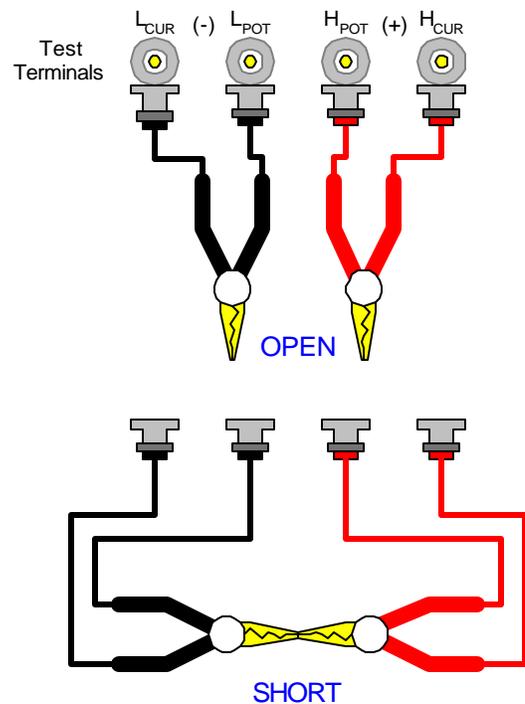


Figure 13: Open/Short

## Load Correction

Load Correction is a compensation technique which uses a load whose impedance is accurately known and applies a correction to measurements of similar components to substantially improve measurement accuracy. The purpose being to correct for non-linearity of the measuring instrument and for test fixture or lead effects which may be dependent on the test frequency, test voltage, impedance range, or other factors. Criteria for selecting the appropriate load include:

- a. Load whose impedance value is accurately known.
- b. Load whose impedance value is very close to the DUT (this ensures that the measuring instrument selects the same measurement range for both devices).
- c. Load whose impedance value is stable under the measurement conditions.
- d. Load whose physical properties allow it to be connected using the same leads or fixture as the DUT.

A prerequisite for load correction is to perform a careful open/short compensation as previously discussed. This feature, found on a number of QuadTech LCR Meters, provides for an automatic load correction. The load's known value is entered into memory, the load then measured, and this difference then applied to ongoing measurements.

$$Z_{\text{actual}} = Z_{\text{measure}} \pm \Delta Z$$

$\Delta Z$  = the difference between the known and the measured value of the load.

Through the use of load correction it is possible to effectively increase the accuracy of the measuring instrument substantially, but this is only as good as the known accuracy of the load used in determining the correction.

# Capacitance Measurements

Capacitors are one of the many components used in electronic circuits. The basic construction of a capacitor is a dielectric material sandwiched between two electrodes. The different types of capacitors are classified according to their dielectric material. Figure 14 shows the general range of capacitance values according to their dielectric classification. Capacitance  $C$ , dissipation factor  $D$ , and equivalent series resistance ESR are the parameters usually measured.

Capacitance is the measure of the quantity of electrical charge that can be held (stored) between the two electrodes. Dissipation factor, also known as loss tangent, serves to indicate capacitor quality. And finally, ESR is 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  $ESR = D/\omega C$  where  $\omega = 2\pi f$ .

## Series or Parallel

Advances in impedance measurement instrumentation and capacitor manufacturing techniques coupled with a variety of applications has evolved capacitor test into what might be considered a complex process. A typical equivalent circuit for a capacitor is shown in Figure 15. In this circuit,  $C$  is the main element of capacitance.  $R_s$  and  $L$  represent parasitic components in the lead wires and electrodes and  $R_p$  represents the leakage between the capacitor electrodes.

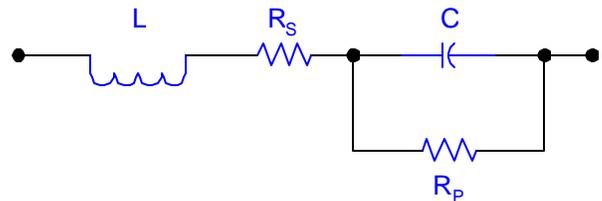


Figure 15: Capacitor Circuit

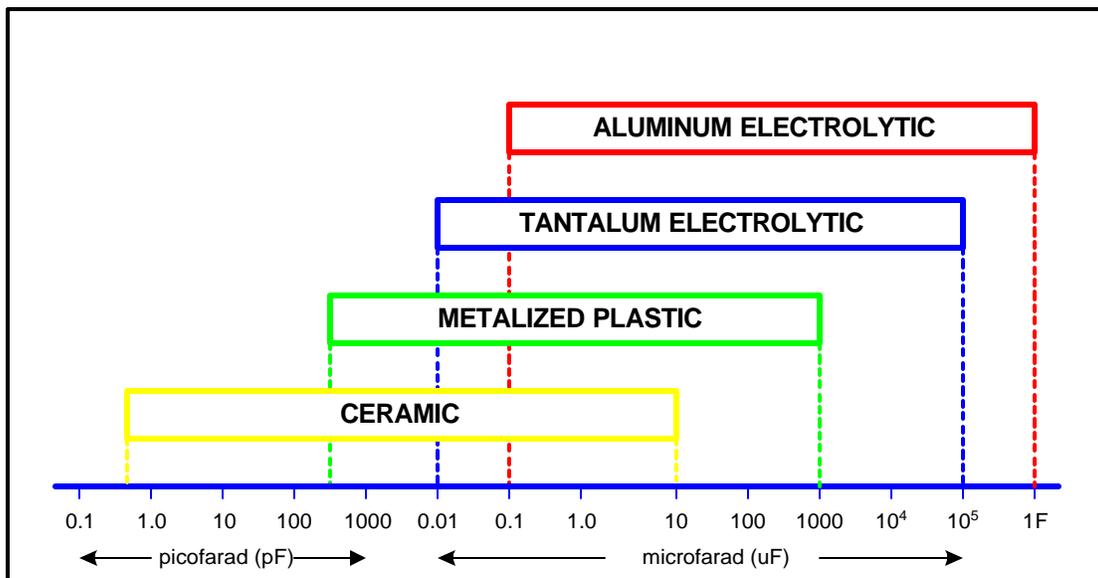


Figure 14: Capacitance Value by Dielectric Type

When measuring a capacitor these parasitics must be considered. Measuring a capacitor in series or parallel mode can provide different results, how they differ can depend on the quality of the device, but the thing to keep in mind is that 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 and  $R_s$  and  $R_p$ . For example, suppose the capacitor modeled in Figure 16 has a small value.

Remember reactance is inversely proportional to  $C$ , so a small capacitor yields large reactance which implies that the effect of parallel resistance ( $R_p$ ) has a more significant effect than that of  $R_s$ . Since  $R_s$  has little significance in this case the parallel circuit mode should be used to more truly represent the effective value. The opposite is true in Figure 17 when  $C$  has a large value. In this case the  $R_s$  is more significant than  $R_p$  thus the series circuit mode become appropriate. Mid range values of  $C$  requires a more precise reactance-to-resistance comparison but the reasoning remains the same.

The rule of thumb for selecting the circuit mode should be based on the impedance of the capacitor:

- \* Above approximately  $10\text{ k}\Omega$  - use parallel mode
- \* Below approximately  $10\Omega$  - use series mode
- \* Between these values - follow manufacturers recommendation

#### Translated to a 1kHz test:

Use  $C_p$  mode below  $0.01\ \mu\text{F}$  and  $C_s$  mode above  $10\ \mu\text{F}$ ; and again between these values either could apply and is best based on the manufacturers recommendation.

If  $C = \text{Low}$  then  $X_c = \text{High}$  and  $R_p$  becomes the most significant resistance

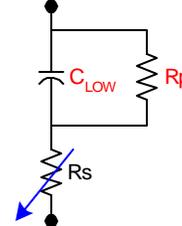


Figure 16:  $R_p$  more significant

If  $C = \text{High}$  then  $X_c = \text{Low}$  and  $R_s$  becomes the most significant resistance

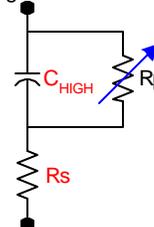


Figure 17:  $R_s$  more significant

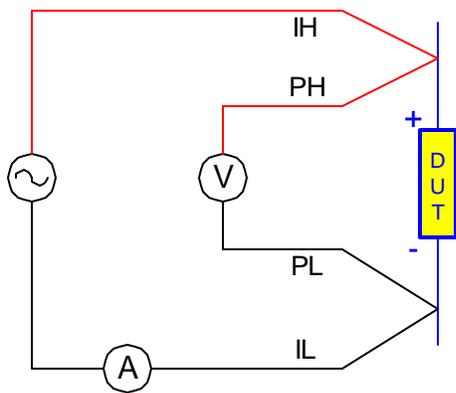
The menu selection, such as that on the QuadTech 7000 Series LCR Meter, makes mode selection of  $C_s$ ,  $C_p$  or many other parameters easy with results clearly shown on the large LCD display.

### Measuring Large and Small Values of Capacitance

High 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,

can be used to reduce effects of stray capacitance. This is a help to small value capacitors but not the large value capacitors because the lead inductance and resistance still remains.

For the best of both worlds a four terminal configuration, discussed earlier and shown in Figure 18, (often termed Kelvin) can be used to reduce the effects of lead impedance for high value capacitors. Two of the terminals serve for current sourcing to the device under test, and two more for voltage sensing. This technique simply removes errors resulting from series lead resistance and provides considerable advantage in low impedance situations.

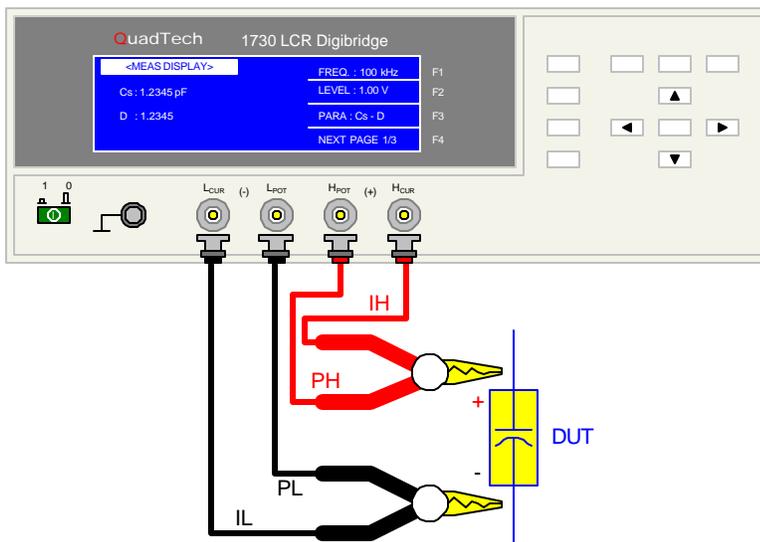


**Figure 18a: 4-Terminal to DUT**

Besides a 4-terminal connection made as close as possible to the device under test, a further enhancement to measurement integrity is an

OPEN/SHORT compensation by the measuring instrument. The open/short compensation when properly performed is important in subtracting out effects of stray mutual inductance between test connections and lead inductance. The effect of lead inductance can clearly increase the apparent value of the capacitance being measured. Open/Short compensation is one of the most important techniques of compensation used in impedance measurement instruments. Through this process each residual parameter value can be measured and the value of a component under test automatically corrected.

One of the most important things to always keep in mind is a concerted effort to achieve consistency in techniques, instruments, and fixturing. This means using the manufacturers recommended 4-terminal test leads (shielded coax) for the closest possible connection to the device under test. 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 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.



**Figure 18b:  
4-Terminal to DUT  
1730 LCR Meter  
and  
Kelvin Clip Leads**

## Equivalent Series Resistance (ESR)

Questions continually arise concerning the correct definition of the ESR (Equivalent Series Resistance) of a capacitor and, more particularly, the difference between ESR and the actual physical series resistance (which we'll call  $R_s$ ), the ohmic resistance of the leads and plates or foils. Unfortunately, ESR has often been misdefined and misapplied. The following is an attempt to answer these questions and clarify any confusion that might exist. Very briefly, ESR is a measure of the total lossiness of a capacitor. It is larger than  $R_s$  because the actual series resistance is only one source of the total loss (usually a small part).

At one frequency, a measurement of complex impedance gives two numbers, the real part and the imaginary part:  $Z = R_s + jX_s$ . At that frequency, the impedance behaves like a series combination of an ideal resistance  $R_s$  and an ideal reactance  $X_s$  (Figure 19). If  $X_s$  is negative, the impedance is capacitive and the reactance can be replaced with capacitance as shown in equation 8.

$$8: X_s = \frac{-1}{\omega C_s}$$

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

$$\text{ESR} = R_s = \text{Real part of } Z$$

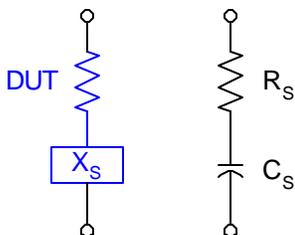


Figure 19: Real Part of Z

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

$$\begin{aligned} 9: D &= \frac{\text{energy lost}}{\text{energy stored}} \\ &= \frac{\text{Real part of } Z}{(-\text{Imaginary part of } Z)} \\ &= \frac{R_s}{(-) X_s} \\ &= R_s \omega C \\ &= (\text{ESR}) \omega C \end{aligned}$$

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, if one put a pure resistance in parallel with a pure capacitance (Figure 20a) creating a lossy capacitor, the ESR of the combination is the Real part of  $Z = \text{Real part of equation 10 as shown in Figure 20b}$ .

$$10: \frac{1}{\frac{1}{R_p} + j\omega C_p} = \frac{R_p}{1 + \omega^2 C_p^2 R_p^2}$$

From Figure 20a, however, it is obvious that there is no actual series resistance in series with the capacitor. Therefore  $R_s = 0$ , but  $\text{ESR} > 0$ , therefore  $\text{ESR} > R_s$ .

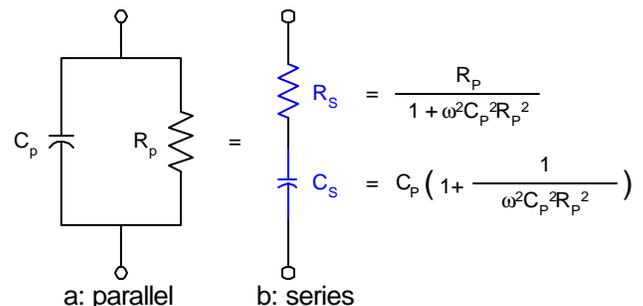
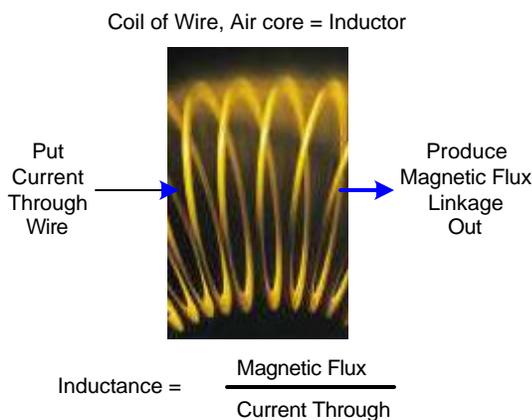


Figure 20: ESR

# Inductance Measurements

An inductor is a coiled conductor. It is a device for storing energy in a magnetic field (which is the opposite of a capacitor that is a device for storing energy in an electric field). An inductor consists of wire wound 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.



## Series or Parallel

As with capacitor measurements, inductor measurements can be made in either a series or parallel mode, use of the more suitable mode results in a value that equals the actual inductance. In a typical equivalent circuit for an inductor, the series resistance ( $R_s$ ), represents loss of the copper wire and parallel resistance ( $R_p$ ) represents core losses as shown in Figure 21.

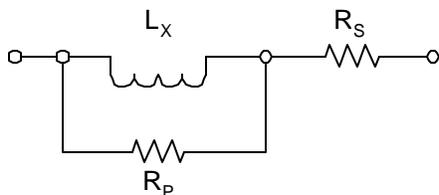


Figure 21: Inductor Circuit

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 the appropriate choice. 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.

The most important thing to remember whenever a measurement correlation problem occurs, is to use the test conditions specified by the component manufacturer. Independent of any series/parallel decision, it is not uncommon for different LCR meters to give different measured results. One good reason for this is that inductor cores can be test signal dependent. 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 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 get an accurate inductance measurement, the inductor must be tested under actual (real life) conditions for current flowing through the coil. This cannot always be accomplished with the typical AC source and a standard LCR meter as the typical source in an LCR meter is normally only capable of supplying small amounts of current ( $<1\text{mA}$ ). 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 is 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 not being constant so the current is not constant. A voltage leveling circuit would monitor the voltage across the inductor and continually adjust the programmed source voltage in order to keep the voltage across the inductor constant.

Since it is possible to apply large values of current and voltage to an inductor, CAUTION must be taken when the current through an inductive circuit is suddenly interrupted because a voltage transient then occurs across the open circuit. Put another way, if the current could be instantly switched off, then the voltage would in theory become infinite. This does not occur because the high voltage develops an arc across the switch as contact is broken, keeping  $di/dt$  from becoming infinite. This does not however prevent the voltage from increasing 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. Refer to Figure 22.

## 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 ( $R_s$ , 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 ( $R_s$ ) and the impedance value of the device. The source impedance is normally between  $5\Omega$  and  $100\text{k}\Omega$ .

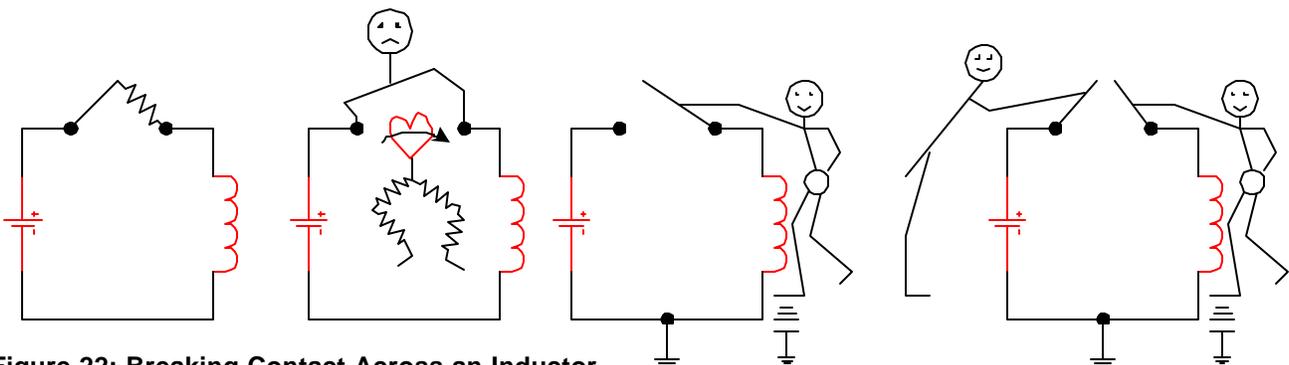


Figure 22: Breaking Contact Across an Inductor

## 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 ACR. 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 (DF) of the device under test (DUT). (Refer to Figure 23).

## Loss

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. Which means as frequency increases, the copper loss decreases. Copper loss is typically measured using an inductance analyzer with DC resistance (DCR) measurement capability 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. Refer to Figure 24.

Hysteretic Loss is proportional to the area enclosed by the hysteresis loop and to the rate at which this loop is transversed (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.

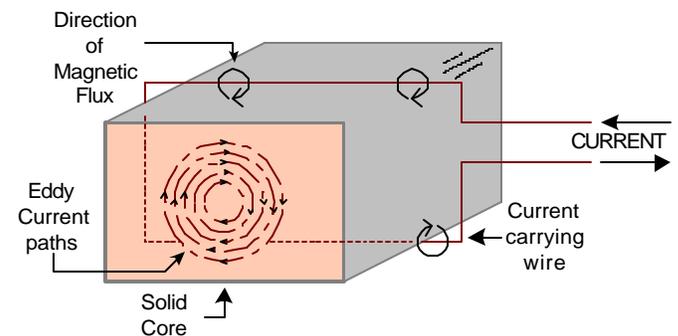


Figure 24: Eddy Currents induced in an iron core

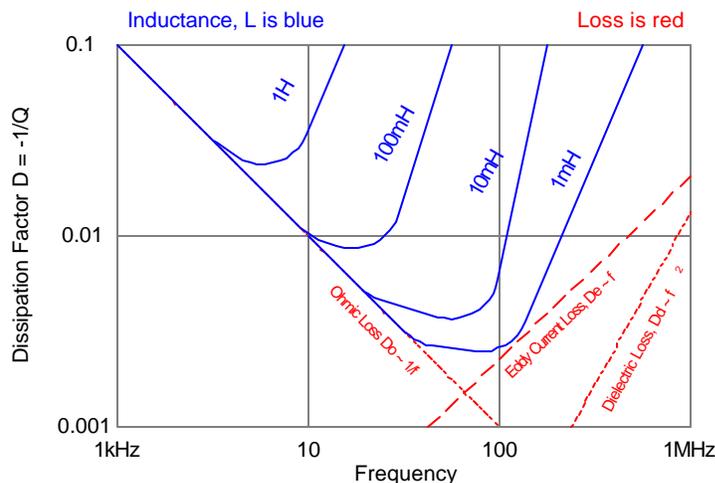


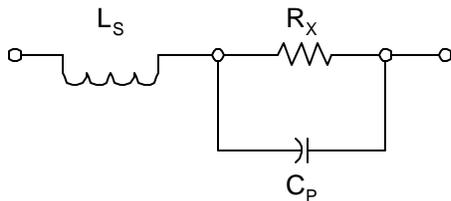
Figure 23: Factors of Total Loss (Df)

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

Resonance Factor
 $D_o$  Ohmic Loss
 $D_e$  Eddy Current Loss
 $D_d$  Dielectric Loss

# Resistance Measurements

Of the three basic circuit components, resistors, capacitors and inductors, resistors cause the least 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 to this, 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. The thing to keep in mind is that if resistors are used in high frequency circuits they will have both real and reactive components. This can be modeled as shown in Figure 25, with a series inductance ( $L_s$ ) and parallel capacitance ( $C_p$ ).



**Figure 25: Resistor Circuit**

For example, in the case of wire-wound resistors (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  $1k\Omega$ ) 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 as discussed earlier.

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  $M\Omega$ ) 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  $R$ .

# Precision Impedance Measurements

QuadTech manufactures several instruments for the measurement and analysis of passive component parameters. The 7000 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 only by high priced, difficult to use, manually balanced impedance bridges and meters.



Figure 26: 7400 Precision LCR Meter

## Measurement Capability

The measurements of highest precision in a standards lab are 1:1 comparisons of similar impedance standards, particularly comparisons between standards calibrated at the National Institute of Standards and Technology (NIST) and similar reference standards. This type of measurement requires an instrument with high measurement resolution and repeatability in order to detect parts-per-million (ppm) differences rather than instruments with extreme, direct-reading accuracy. 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 7000 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  $1/(\text{square root of } N)$  where  $N$  is the number of measurements averaged. Thus, an average of 5 measurements or more typically reduces the

standard deviation to 5 ppm. It is therefore possible to measure the difference between two impedances to approximately 10 ppm with the 7000. Averaging many measurements takes time, however an automatic impedance meter like the 7000 can take hundreds of averaged measurements in the time it takes to balance a high-resolution, manual bridge.

Measurement precision and confidence can be further improved by using the 7000's median measurement mode. In the median measurement mode, the instrument makes three measurements rather than one and discards the high and low results. The remaining median measurement value is used for display or further processing (such as averaging). Using a combination of averaging and median measurements not only increases basic measurement precision, but will also yield measurements that are independent of a large errors caused by line spikes or other non-Gaussian noise sources.

The ppm resolution of the 7000 is also not limited to values near full scale as is typically true on six-digit, manual bridge readouts. In the case of a manually balanced bridge, the resolution of a six-digit reading of 111111 is 9 ppm. The 7000 does not discriminate against such values; it has the same 0.1 ppm resolution at all values of all parameters including dissipation factor (D) and quality factor (Q), the tangent of phase angle.

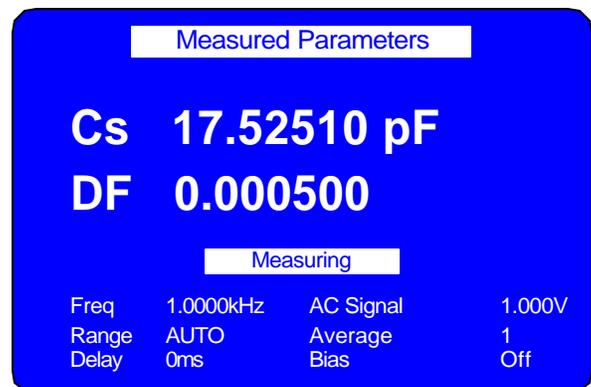
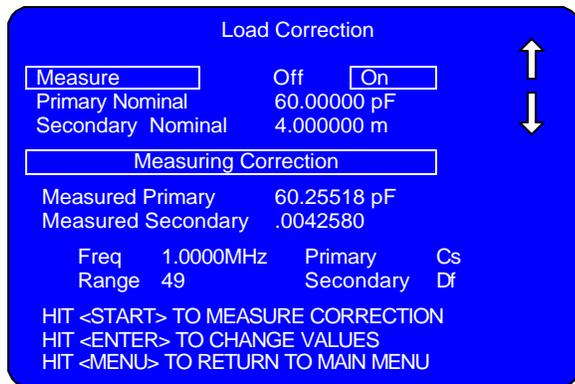


Figure 27: Parts Per Million Resolution

The 7000 instrument also provides a unique load correction feature that allows the user to enter known values for both primary and secondary parameters, as illustrated in the load correction display of Figure 28. The instrument measures these values and automatically applies the correction to ongoing measurements.



**Figure 28: Entry of Values for Load Correction**

Obviously, automatic instruments such as the QuadTech 7000 have the significant advantage of speed, since a balancing procedure is not required. Balancing manual ac bridges is tiresome, time consuming and frequently requires highly skilled personnel. Another advantage of programmable instruments is the ability to create a fully automated system by utilizing the instrument's RS-232 and IEEE-488.2 bus interface capability. With a computer based system, correction calculations can be made without the chance of human errors, especially the all too common recording problems with + and - signs.

## Instrument Accuracy

In determining how the instrument's measurement capability is defined, take a look at the specified accuracy of the instrument. Also, to maintain the accuracy and repeatability of measurements, the calibration procedure should be investigated. A DUT's measured value is only as accurate as the instrument's calibrated value (plus fixture effects).

## Basic Accuracy

Manufacturers of LCR meters specify basic accuracy. This is the best-case accuracy that can be expected. Basic accuracy does not take into account error due to fixturing 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, high accuracy which equates to 1 measurement/second, and a DUT impedance between 10Ω and 100kΩ. Typical LCR meters have a basic accuracy between ±0.01% and ±0.5%.

## Actual Accuracy

If the measurements are to be made outside of "optimum" conditions for basic accuracy, the actual accuracy of the measurement needs to be determined. This is done using a formula or by looking at a graph of accuracy versus impedance and frequency (refer to Figure 31).

It is also important to understand that the measurement range is really more a display range. For example an LCR will specify a measurement range of 0.001nH to 99.999H this does not mean you can accurately measure a 0.001nH inductor or a 99.999H inductor, but you can perform a measurement and 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. There are addition errors including dissipation factor Df of the DUT, internal source impedance and ranges of the instrument, that effect accuracy.

## Factors Affecting Accuracy Calculations

### DUT Impedance

High impedance measurements increase the error because it is difficult to measure the current flowing through the DUT. For example if the impedance is greater than  $1\text{M}\Omega$  and the test voltage is one volt there will be less than  $1\text{mA}$  of current flowing through the DUT. The inability to accurately measure the current causes an increase in error.

Low impedance measurements have an increase in error because it is difficult to measure the voltage across the DUT. Most LCR Meters have a resistance in series with the source of  $100\text{k}$  to  $5\text{ ohms}$ . As the impedance of the DUT approaches the internal source resistance the voltage across the DUT drops proportionally. If the impedance of the DUT is significantly less than the internal source resistance then the voltage across the DUT becomes extremely small and difficult to measure causing an increase in error.

### Frequency

The impedance of reactive components is also proportional to frequency and this must be taken into account when it comes to accuracy. For example, measurement of a  $1\mu\text{F}$  capacitor at  $1\text{ kHz}$  would be within basic measurement accuracy where the same measurement at  $1\text{MHz}$  would have significantly more error. Part of this is due to the decrease in the impedance of a capacitor at high frequencies however there generally is increased measurement error at higher frequencies inherent in the internal design of the LCR meter.

### Resolution

Resolution must also be considered for low value measurements. If trying to measure  $0.0005\text{ ohms}$  and the resolution of the meter is  $0.00001\text{ ohms}$  then the accuracy of the measurement cannot be any better than  $\pm 2\%$  which is the resolution of the meter.

## 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  $1\text{kHz}$ . At lower frequencies measurement times can take even longer because the measurement speed refers to the integration or averaging of at least one complete cycle of the stimulus voltage. For example, if measurements are to be made at  $10\text{Hz}$ , the time to complete one cycle is  $1/\text{frequency} = 1/10\text{Hz} = 100\text{ milliseconds}$ . Therefore the minimum measurement speed would be  $100\text{ms}$ .

## Dissipation Factor (D) or Quality Factor (Q)

D and Q are reciprocals of one another. The importance of D or Q is the fact that they represent the ratio of resistance to reactance or vice versa. This means that 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 greater than the other, the phase angle will approach  $\pm 90^\circ$  or  $0^\circ$ . As shown in Figure 29, even small changes in phase at  $-90^\circ$  result in large changes in the value of resistance, R.

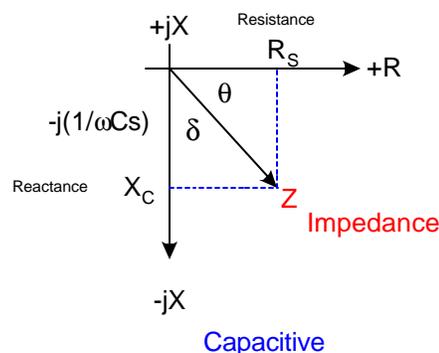


Figure 29: Phase Diagram for Capacitance

## Example: Accuracy Formula

7600 Precision LCR Meter

Test Conditions:

- 1pF Capacitor at 1MHz
- 1VAC signal
- Auto Range
- Non-Constant Voltage
- Slow Measurement Speed
- Df of 0.001

Basic Accuracy of the 7600 is  $\pm 0.05\%$

Accuracy Formula for Slow Mode R, L, C, X, G, B, |Z|, and |Y| is given in Equation 11.

$V_S$  = Test voltage in voltage mode,

=  $I * Z_m$  in current mode\*

$Z_m$  = Impedance of DUT

$F_m$  = Test frequency

$K_t$  = 1 for 18° to 28°C

= 2 for 8° to 38°C

= 4 for 5° to 45°C

$V_{FS} = 5.0$  for  $1.000V < V_S \leq 5.000V$

1.0 for  $0.100V < V_S \leq 1.000V$

0.1 for  $0.020V \leq V_S \leq 0.100V$

For  $Z_m > 4 * Z_{RANGE}$  multiply A% by 2

For  $Z_m > 16 * Z_{RANGE}$  multiply A% by 4

For  $Z_m > 64 * Z_{RANGE}$  multiply A% by 8

\*: For  $I * Z_m > 3$ , accuracy is not specified

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

Equation 11: 7600 Accuracy Formula

The impedance range ( $Z_{RANGE}$ ) is specified in this table:

	In Voltage Mode	In Current Mode
$Z_{RANGE} =$	100kΩ for $Z_m \geq 25k\Omega$	400Ω for $I < 2.5mA$
	6kΩ for $1.6k\Omega \leq Z_m < 25k\Omega$	25Ω for $I > 2.5mA$
	6kΩ for $Z_m > 25k\Omega$ and $F_m > 25kHz$	
	400Ω for $100\Omega \leq Z_m < 1.6k\Omega$	
	400Ω for $Z_m > 1.6k\Omega$ and $F_m > 250kHz$	
	25Ω for $Z_m < 100\Omega$	

The Calculated Accuracy using the formula in Equation 11 is 3.7% substituting the values listed herein.

$K_t = 1$

$Z_m = 1 / (2\pi * \text{frequency} * C)$

$= 1 / (2\pi * 1000000 * 1 \times 10^{-12})$

$= 159 \text{ kohms}$

$Z_{RANGE} = 400 \text{ ohms}$

$V_{fs} = 1$

Multiply A% = 8

A% = 0.46%

Multiply A% times 8 due to  $Z_m > 64$  times

$Z_{RANGE}$

$$A\% = 0.46\% * 8 = 3.68\%$$

Refer to Equation 12 to fill in the numbers.

**Equation 12: Completed 7600 Accuracy Formula**

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

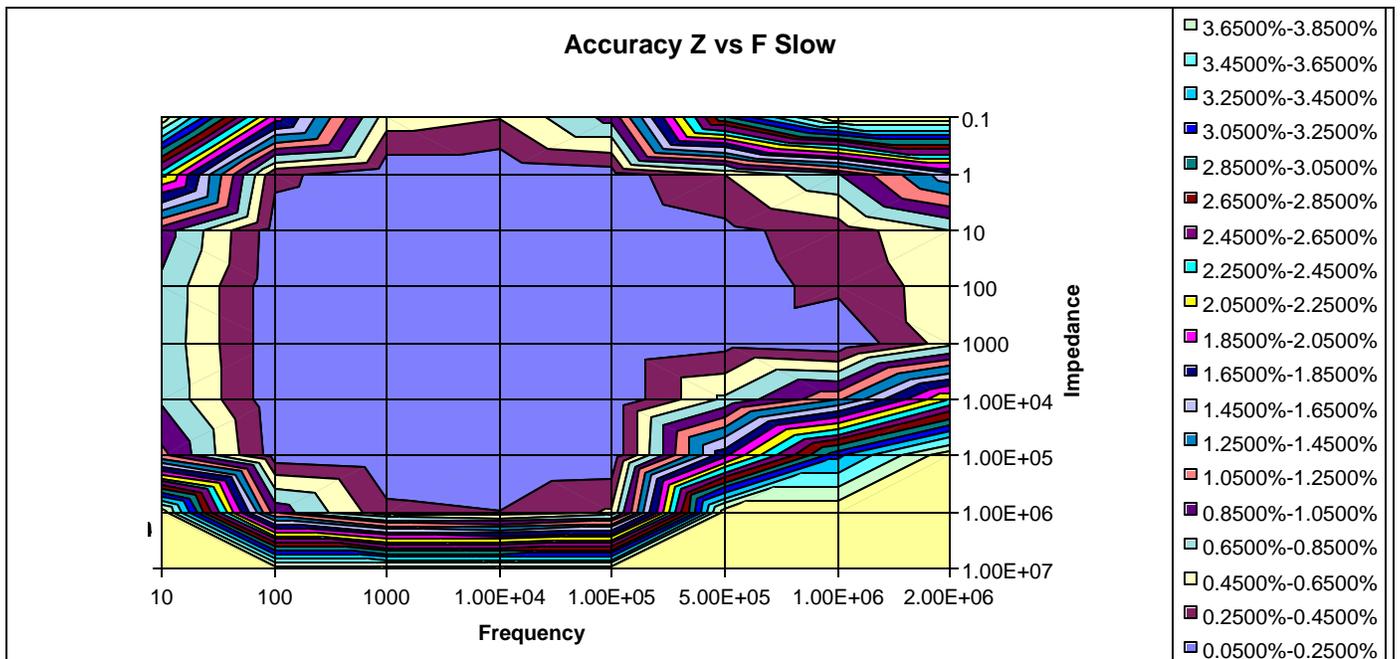
**Example 7600 Accuracy Graph**

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:

$$Z = X_s = 1/(2\pi \times \text{frequency} \times \text{capacitance})$$

$$Z = X_s = 1/(2\pi \times 1,000,000 \times 0.000,000,000,001) = 159\text{kohms}$$

Use the graph in Figure 30 and substitute Z for R. If we find the position on the graph for an impedance value of 159kohms 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%.



**Figure 30: 7600 Accuracy Plot**

# Materials Measurements

## Materials Measurement

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.



Figure 31: QuadTech 7000 Meter with LD-3 Cell

### Definitions

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

$$K = \epsilon' = \epsilon_r$$

and

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

The complex relative permittivity is:

$$\epsilon_r^* = \frac{\epsilon}{\epsilon_0} = \epsilon_r' - j(\epsilon_r'')$$

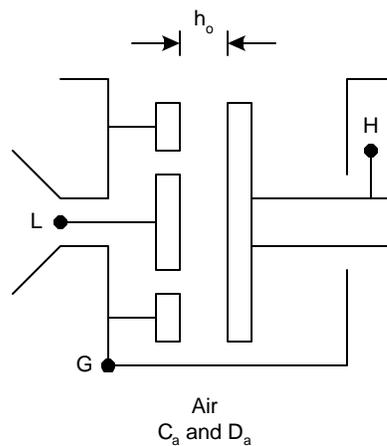
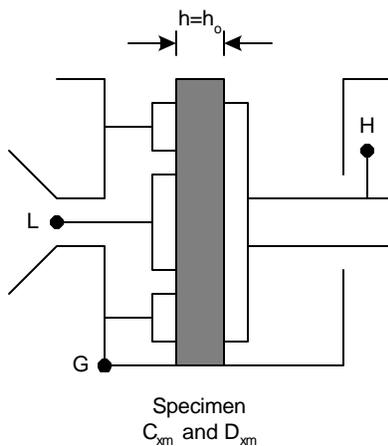


Figure 32: Contact Electrode

where  $\epsilon_0$  is the permittivity of a vacuum, and  $\epsilon$  the absolute permittivity.

$$\epsilon_0 = 0.08854 \text{ pF/cm}$$

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

$$C = K_a \epsilon_0 \text{ Area / spacing}$$

where  $K_a$  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. Refer to Figure 32. 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  $h_m$ .

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  $D_a$  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.

### The 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.

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  $C_a$  and  $D_a$ . Note the micrometer setting as  $h_m$  which can be corrected with the micrometer zero calibration,  $h_{m0}$  to get:

$$h_o = (h_m + h_{m0})$$

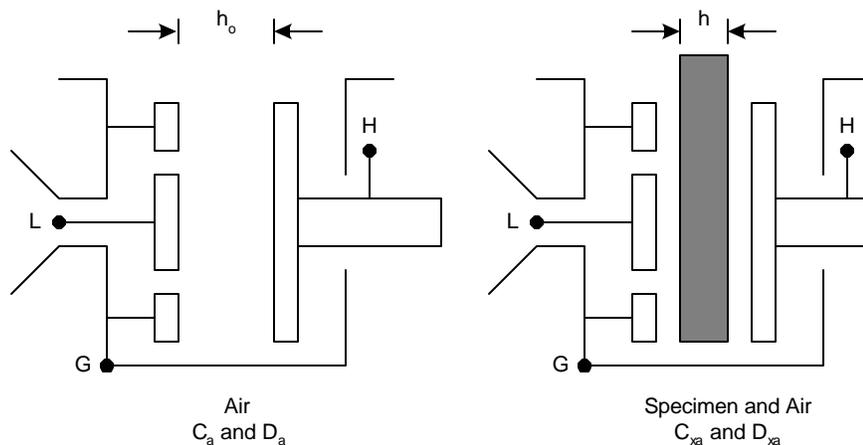
The sample is inserted and measured as  $C_{xa}$  and  $D_{xa}$ . Calculate:

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

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

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

**Figure 33:  
Air Gap Method**



The factor  $(1 + D_x^2)$  converts the series value of  $C_x$  to the equivalent parallel value and is not necessary if  $D_x$  is small. The factor of 1.0005 corrects for the dielectric constant of air (if dry). The formula for  $D_x$  assumes that the true  $D$  of air is zero and it makes a correction for a constant  $D$  error in the instrument.

### The 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.

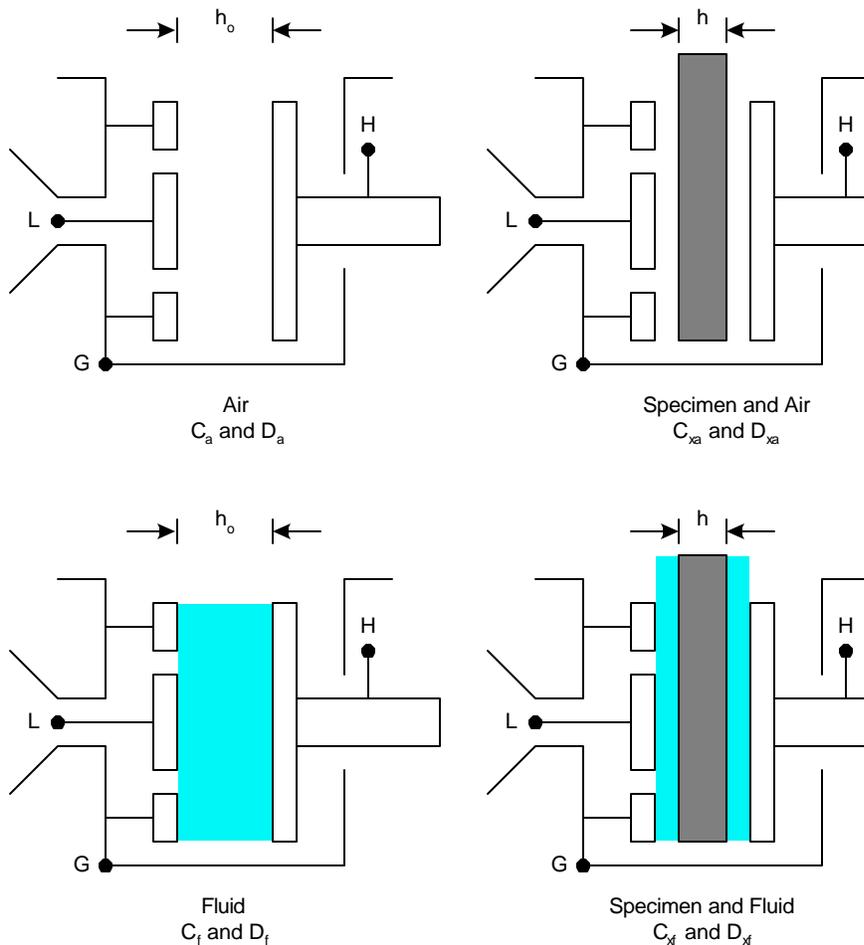
The four measurements of series capacitance and  $D$  are outlined in the Figure 34. Note the spacing is the same for all measurements and should be just slightly more than the specimen thickness. The accuracy will be limited mainly by the accuracy of the measurements made.

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  $C_a$ .



**Figure 34: Two Fluid Method**

If  $D_x$  is close to  $D_f$  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  $D_x$  is very small use:

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

which makes a zero D correction.

From the above results calculate:

$$K_x = \left( \frac{h}{h_0} \right) \left( \frac{C_{xser}}{C_a} \right) \left( \frac{1.0005}{1 + D_x^2} \right)$$

As before, the factor of 1.0005 corrects for the dielectric constant of air (if dry) and the factor  $(1 + D_x^2)$  converts  $C_x$  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 ( $C_a$  and  $D_a$ ), is measured first and then that of the liquid ( $C_{xm}$  and  $D_{xm}$ )

Determine  $K_x$  and  $D_x$ :

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

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

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

# Recommended LCR Meter Features

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 in 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 ( $R_s$ , 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 ( $R_s$ ) 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), suscep-

tance (B), phase angle ( $\theta$ ) 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

A further enhancement to accuracy can be obtained 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 standard data communication interface for connection to 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 7000 series instruments have seven display modes: measured parameters, deviation from nominal, % deviation from nominal, Pass/Fail, Bin Summary, Bin Number and No Display. Refer to Figure 35. Figure 36 illustrates three of the 7000 Series display modes.

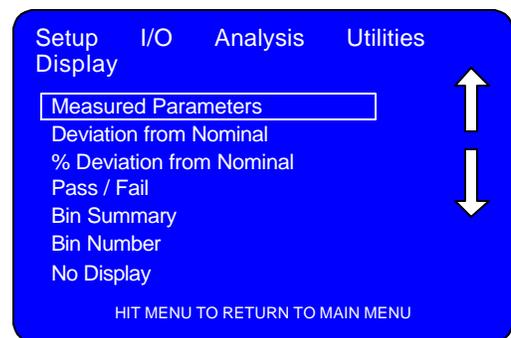


Figure 35: 7600 Display Menu

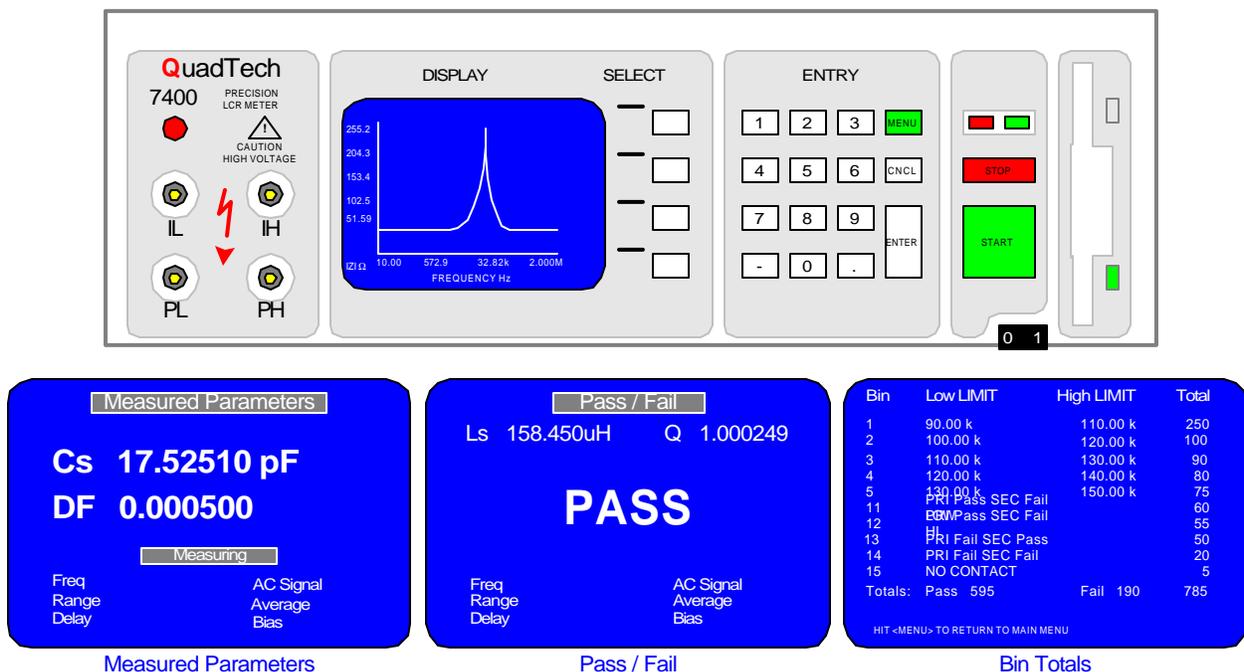
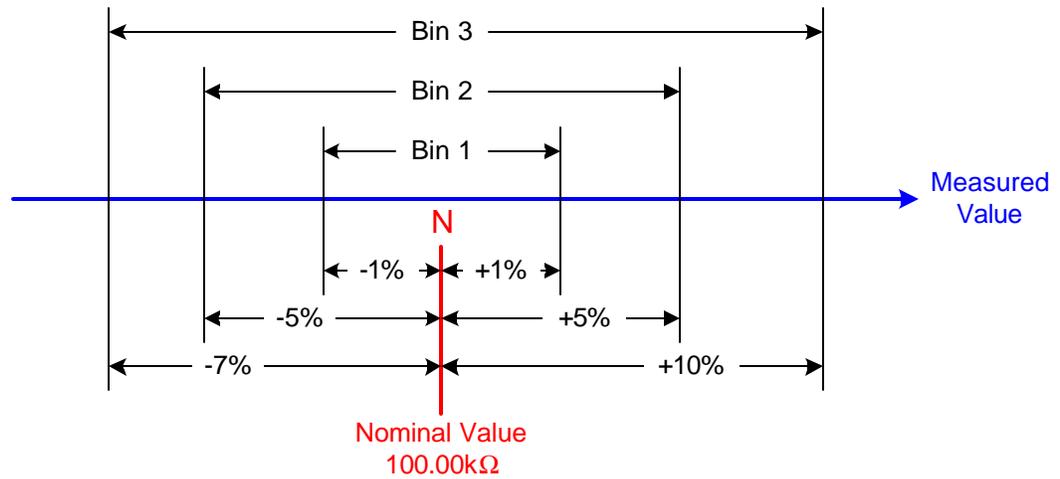


Figure 36: Example 7600 Display Modes



**Figure 37:**  
Nested Limits

### Binning

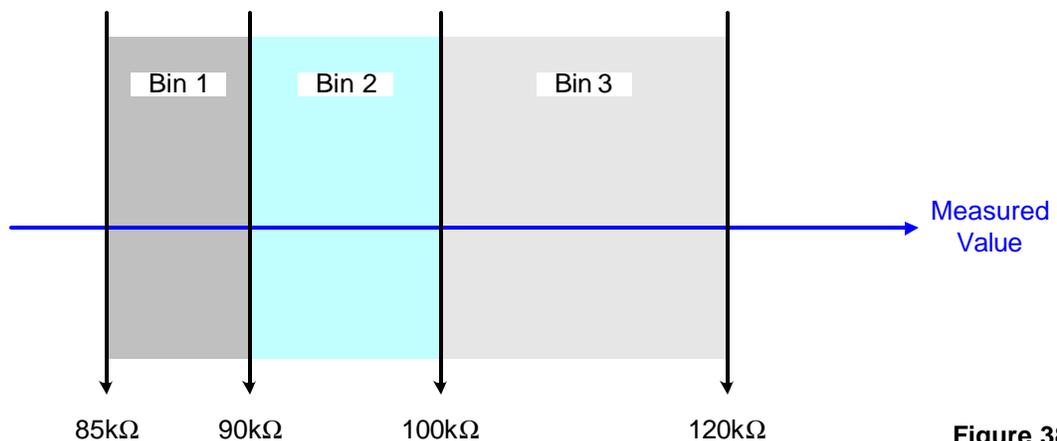
A necessary production application, binning sorts components by test results quickly by a predetermined value set by the test engineer. Two of the most common methods of sorting results into bins are using nested limits or sequential limits.

#### 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 in Figure 37. Note that the limits do not have to be symmetrical (Bin 3 is -7% and +10%).

#### Sequential Limits

Sequential limits are a natural choice when sorting components by absolute value. Figure 38 illustrates the use of sequential limits for a total of three bins. 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 38:**  
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 QuadTech 7000 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).

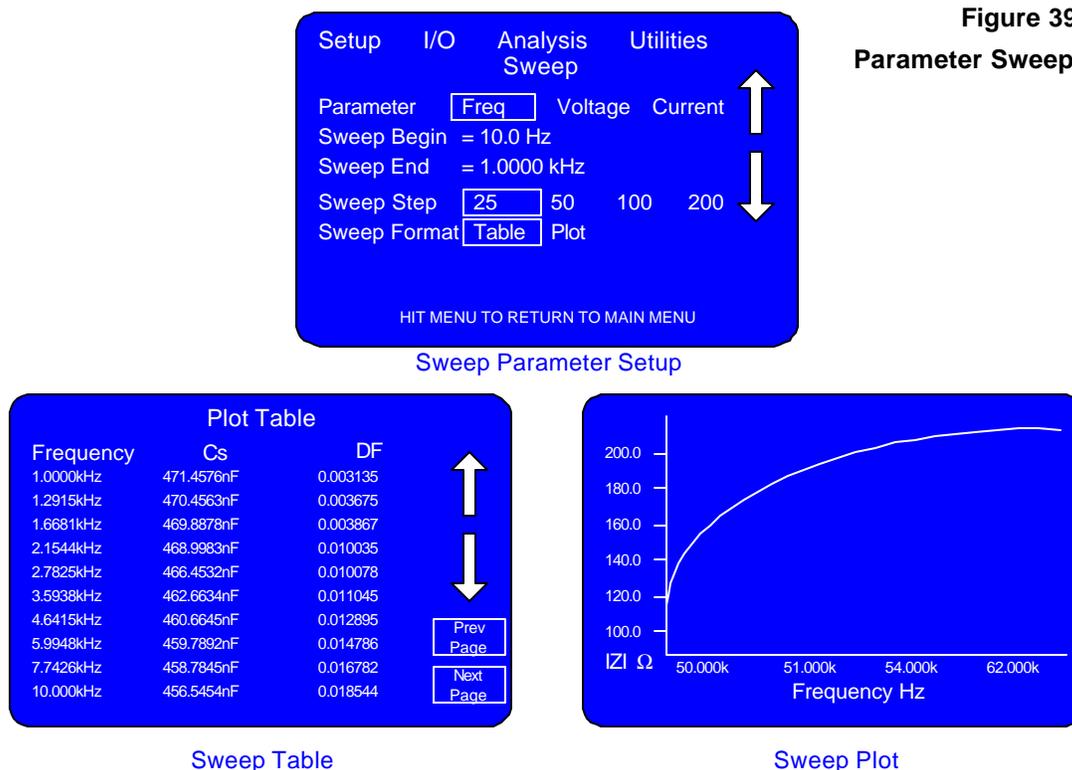
Figure 39 illustrates the parameter sweep function of the 7000 Series instrument.

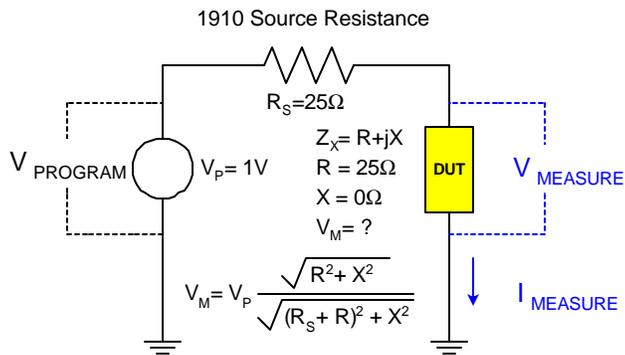
## Bias Voltage and Bias Current

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 a constant source impedance, will provide a source resistance ( $R_s$ ) that will hold the current constant. Therefore one knows what the voltage at the DUT will be.  $R_s$  is in series with the ac output such that the programmed voltage is 1V but the voltage to the test device is 0.5V. Refer to Figure 40.





**Figure 40: Constant Source Impedance**

### 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.

**Figure 41: Digibridge Family: 1689 & 1689M**



# Examples of High Performance Testers

Examples of passive component measuring instrumentation manufactured by QuadTech, Inc of Maynard Massachusetts is provided herein. Included are: Digibridges, Precision LCR Meters and Impedance Analyzers.

## Digibridges

The 1600 and 1700 Series digital bridges are high performance passive component testers.

## 1600 Series

### Common Features

- Full five digit display for primary L,C & R
- Four digit display for secondary D, Q
- Continuous or Triggered Measurement Mode
- Open & Short Circuit Compensation
- DC Bias: Internal to 2V, External to 60V
- Auto Ranging with Manual Hold
- Pass/Fail Bins for Component Sorting
- Charged Capacitor Protection
- Optional IEEE 488 and Handler Interfaces
- Full Range of Accessory Options

## 1659 LCR Digibridge

- Measurement Parameters: R/Q, L/Q, C/R, C/D
- Test Frequency: 100Hz, 120Hz, 1kHz, 10kHz
- Accuracy: 0.1% LCR; 0.0005 DQ
- Applied Voltage: 0.3V maximum
- 2, 4 or 8 Measurements per second

## 1689/89M LCR Digibridge

- Measurement Parameters: R/Q, L/Q, C/R, C/D
- Programmable Test Frequency: 12Hz to 100kHz
- Accuracy: 0.02% LCR; 0.0001 DQ
- Programmable Test Voltage: 5mV to 1.275V
- 1689: Up to 30 measurements/second\*
- 1689M: Up to 50 measurements/second\*
- Constant Voltage Mode (25 $\Omega$  Source)
- Median Value Mode

\* With High Speed Option

## 1692 LCR Digibridge



**Figure 42: 1692 Digibridge**

- Measurement Parameters: R/Q, L/Q, C/R, C/D
- Test Frequency: 100Hz, 120Hz, 1kHz, 10kHz and 100kHz
- Accuracy: 0.05% LCR; 0.0003 DQ
- Applied Voltage: 0.3V to 1.0V maximum
- 2, 4 or 8 measurements/second
- Constant Voltage Mode (25 $\Omega$  Source)
- Single Triggered Measurement or 1-10 Averaged

## 1693 LCR Digibridge



**Figure 43: 1693 Digibridge**

- Measurement Parameters: R/Q, L/Q, C/R, C/D, R/X, G/B, Z $\theta$ , Y/ $\theta$
  - 500 Test Frequencies: 12Hz to 200kHz
  - Accuracy: Primary 0.02% L,C,R, G, Z, Y  
Secondary: 0.0002 DQ; 0.01 $^{\circ}$   $\theta$
  - Programmable Test Voltage: 5mV to 1.275V
  - Up to 50 measurements/second\*
  - Constant Voltage Mode (25 $\Omega$  Source)
  - Median Value Mode
- \* With High Speed Option

## 1700 Series

### Common Features

- Guarded 4-Terminal Kelvin Connection
- Selectable Test Voltage & Frequency
- Selectable Measurement Rate
- External DC Bias Voltage
- Full Range of Accessory Options



**Figure 45: 1730 Digibridge**

### 1715 LCR Digibridge



**Figure 44: 1715 Digibridge**

- 11 Measurement Parameters
- Test Frequency: 100Hz, 120Hz, 1kHz & 10kHz
- Basic Accuracy: 0.2% LCR; 0.002 DQ
- Test Signal: 0.25V or 1.0V
- Up to 25 measurements/second
- Programmable Source Impedance
- Open/Short Compensation
- Comparator: Primary/Secondary Hi/Lo Limits
- Binning: 8 Bins Primary/Secondary
- RS-232 Interface, Standard
- IEEE-488 & Handler Interfaces, Optional

### 1730 LCR Digibridge

- 12 Measurement Parameters
- Accuracy: 0.1% LCR; 0.0001 DQ
- 7 Test Frequencies: 100Hz to 100kHz
- Programmable Test Voltage: 10mV to 1.0V
- Up to 62 measurements/second
- Programmable Source Impedance
- IEEE-488 & Handler Interfaces, Standard
- Monitor DUT Voltage & Current
- Storage/Recall of 50 Setups
- Pass/Fail Binning
- Measurement Averaging (1-256)
- Measurement Delay (0-10 seconds)
- DC Bias Voltage: 0-5V
- Automatic Open/Short Zeroing

## Precision LCR Meters

The 1900 and 7000 Series digital LCR meters are precise impedance analyzers with a host of useful functions for component testing and data analysis.

### 1900 Series

#### Common Features

- High Performance, Fast, Production Oriented
- Wide Frequency Range
- Automatic Test Sequencing
- Internal, External or Manual Trigger
- Programmable Source Impedance
- Constant Voltage Mode (Voltage Leveling)
- IEEE-488, RS232 & Handler Interfaces, Std.
- Built-In Automatic Calibration Procedure
- Cable Compensation (1M, 2M, no cable)
- Self Test Routine- Verify Instrument Operation



**Figure 46: 1910 Inductance Analyzer**

### 1910 Inductance Analyzer

- 20 Measurement Parameters
- Basic Accuracy: 0.1% LCR; 0.001 DQ
- 27,000 Test Frequencies: 20Hz to 1MHz
- Programmable Test Voltage: 20mV to 1.0V
- Up to 40 measurements/second
- DC Bias Current: 1mA to 1A
- DC Resistance Measurements: 0.1m $\Omega$ -100k $\Omega$
- Monitor DUT Voltage & Current
- Storage/Recall of 30 Single tests, 10 Sequential
- 14 Pass/Fail Bins
- Measurement Averaging (1-1000)
- Measurement Delay (0 to 1000 ms)
- Open/Short Zeroing
- Displays Usage & Calibration Data

### 1920 Precision LCR Meter

- 20 Measurement Parameters
- Basic Accuracy: 0.1% LCR; 0.001 DQ
- 27,000 Test Frequencies: 20Hz to 1MHz
- Programmable Test Voltage: 20mV to 1.0V
- Up to 40 measurements/second
- DC Bias Voltage: 0V to 2.0V, Internal
- DC Resistance Measurements: 0.1m $\Omega$ -100k $\Omega$
- Monitor DUT Voltage & Current
- Storage/Recall of 30 Single tests, 10 Sequential
- 14 Pass/Fail Bins
- Measurement Averaging (1-1000)
- Measurement Delay (0 to 1000 ms)
- Open/Short Zeroing
- Displays Usage & Calibration Data

### 7000 Series

#### Common Features

- Fast, Precise, Production and R&D Oriented
- Wide Frequency Range
- Programmable Test Voltage & Current
- Graphical and Tabular Display
- Automatic Test Sequencing
- Swept Frequency & Signal Level Measurements
- Internal, External or Manual Trigger
- AutoAcc (Automatic Accuracy Calculation)
- Built-In Calibration Routine
- IEEE-488, RS232, Handler, Parallel Printer and 3.5" Disk Drive Interfaces, Standard
- Internal Storage of Test Setups & Floppy Drive
- Full Range of Accessory Options



**Figure 47: 7400 Precision LCR Meter**

## 7400 Precision LCR Meter

- 14 Measurement Parameters
- Basic Accuracy: 0.05% LCR; 0.0005 DQ
- Programmable Test Frequency: 10Hz to 500kHz
- Programmable Test Voltage: 20mV to 5.0V
- Programmable Test Voltage: 250uA to 100mA
- Up to 40 measurements/second
- DC Bias Voltage: 0V to 2.0V, Internal
- DC Bias Voltage: 0V to 200V, External
- DC Bias Voltage: 0V to 500V, External (7400A)
- Internal Storage/Recall of 25 Setups
- 15 Pass/Fail Bins
- Measurement Averaging (1-1000)
- Measurement Delay (0 to 1000 ms)
- Charged Capacitor Protection
- Displays Usage & Calibration Data

## 7600 Precision LCR Meter

- 14 Measurement Parameters
- Basic Accuracy: 0.05% LCR; 0.0005 DQ
- Programmable Test Frequency: 10Hz to 2MHz
- Programmable Test Voltage: 20mV to 1.0V
- Programmable Test Voltage: 250uA to 100mA
- Up to 25 measurements/second
- DC Bias Voltage: 0V to 2.0V, Internal
- DC Bias Voltage: 0V to 200V, External
- DC Bias Voltage: 0V to 500V, External (7600A)
- Internal Storage/Recall of 25 Setups
- 15 Pass/Fail Bins
- Measurement Averaging (1-1000)
- Measurement Delay (0 to 1000 ms)
- Charged Capacitor Protection
- Displays Usage & Calibration Data



Figure 48: 7600 Precision LCR Meter

## Dedicated Function Test Instruments

In addition to passive component test instrumentation, QuadTech manufactures milliohmmeters, megohmmeters, AC/DC Hipot Testers and Electrical Safety Analyzers. View Product specifications at <http://www.quadtech.com>.

### Milliohmmeters



Figure 49: LR2000 Milliohmmeter

### Megohmmeters



Figure 50: 1865 Megohmmeter

### Hipot Testers



Figure 51: Sentry Plus Series Hipot Tester

### Electrical Safety Analyzers



Figure 52: Guardian 6000 Series Production Safety Analyzer

# Appendix A

# Nationally Recognized Testing Laboratories (NRTL's) and Standards Organizations\*

- Underwriters Laboratories, Inc.  
333 Pfingsten Road Northbrook, Illinois 60062 USA  
Tel: 847-272-8800, <http://www.ul.com>
- American National Standards Institute  
1 West 42nd Street New York, NY 10036  
Tel: 212-642-4900, FAX: 212-398-0023 <http://www.ansi.org>
- British Standards Institution  
389 Chiswick High Road London W4 4AL United Kingdom  
<http://www.bsi.org.uk>
- CENELEC Comité Européen de Normalisation Electrotechnique  
Rue de Stassart, 35 B - 1050 BRUSSELS  
Tel: + 32 2 519 68 71, FAX: + 32 2 519 69 19, <http://www.cenelec.be>
- Canadian Standards Association  
Central Office 178 Rexdale Boulevard Etobicoke (Toronto), Ontario M9W 1R3  
Tel: 416-747-4000 or 1-800-463-6727, <http://www.csa.ca>
- VDE-Verband Deutscher Elektrotechniker  
Merlinstrasse 28 D-63069 Offenbach Federal  
Republic of Germany  
<http://www.vde.de>
- Japanese Standards Association  
1-24, Akasaka 4, Minato-ku Tokyo 107 Japan
- IEC International Electrotechnical Commission  
3, rue de Varembé o PO Box 131 1211 Geneva 20 o Switzerland  
Tel: +41 22 919 02 11 FAX: +41 22 919 03 00, <http://www.iec.ch>
- The Institute of Electrical and Electronic Engineers, Inc  
345 East 47th Street New York, New York 10017  
Tel: 800-678-IEEE <http://www.ieee.org>
- NIST National Institute of Standards and Technology Calibration Program  
Bldg. 820, Room 232, Gaithersburg, MD 20899  
Tel: 301-75-2002, FAX: 301-869-3548, <http://www.nist.gov>
- National Electric Manufacturers Association Standards Publication Office  
2101 L. Street, N.W. Suite 300 Washington, D.C. 20037 USA  
Tel: 202-457-8400 FAX: 202-457-8473, <http://www.nema.org>
- ISO International Standards Organization  
1, rue de Varembé Case postale 56 CH-1211 Genève 20 Switzerland  
Tel: + 41 22 749 01 11, FAX: + 41 22 733 34 30, <http://www.iso.ch>
- OSHA Region 1 Regional Office  
JFK Federal Building, Room E340 Boston, Massachusetts 02203  
Tel: 617-565-9860, FAX: 617-565-9827, <http://www.osha.gov>
- TÜV Rheinland of North America, Inc.  
12 Commerce Road Newton, CT 06470  
Tel: 203-426-0888 <http://www.us.tuv.com>

\* Partial Listing

# Helpful Links

TYPE	NAME	ADDRESS	TELEPHONE	WEBSITE
<b>Parts</b>				
874 Connectors	Gilbert Engineering	5310 West Camelback Rd Glendale AZ 85301	800-528-5567	<a href="http://www.gilbertconnectors.com">http://www.gilbertconnectors.com</a>
874 Connectors	Microwave Distributors	1707-32 Vet. Mem. HW Islandia NY 11722	800-637-4353	<a href="http://microwavedistributors.com">http://microwavedistributors.com</a>
900 Connectors	Mauzy Microwave	2900 Inland Empire Blvd. Ontario CA 91764	909-987-4715	<a href="http://maurymw.com">http://maurymw.com</a>
<b>Equipment</b>				
ATE for Circuit boards	Teradyne Inc	321 Harrison Avenue Boston, MA 02118-2238	617-482-2700	<a href="http://www.teradyne.com">http://www.teradyne.com</a>
Variacs	Power Designs Jerry Voity	P.O. Box 222 14 Commerce Drive Danbury CT 06813	800-682-8235	
Dielectric Cells	Dielectric Products Co. Gerard Gilkie	178 Orchard Street Watertown, MA 02172	617-924-5688	
Dielectric Cells	Vertex Image Products Chuck Bobich	RD#1 Box 117 Yukon PA 15698	724-722-3400	<a href="http://www.verteximage.com">http://www.verteximage.com</a>
<b>Standards</b>				
Inductance, Capacitance & Resistance Standards; Decades, Strobes	IET Labs	10 Dedham Street Newton MA 02461 534 Main Street Westbury, NY 11590	800-475-1211	<a href="http://www.ietlabs.com">http://www.ietlabs.com</a>
<b>Magazines</b>				
Compliance	Canon Communications	11444 W. Olympic Bd. Los Angeles, CA 90064	310-445-4200	<a href="http://www.ce-mag.com">http://www.ce-mag.com</a>
Conformity	Conformity Magazine	531 King Street Littleton, MA 01460	978-486-0888	<a href="http://www.conformity.com">http://www.conformity.com</a>
EDN Electronic Design News Electronic Products	Reed Business Info. (Formerly Cahners) Hearst Business Publishers	275 Washington Street Newton, MA 02458 645 Stewart Avenue Garden City, NY 11530	617-558-4671 516-227-1300	<a href="http://www.e-insite.net/ednmag">http://www.e-insite.net/ednmag</a> <a href="http://www.electronicproducts.com">http://www.electronicproducts.com</a>
EE Times	CMP Media Inc	600 Community Drive Manhasset, NY 11030	516-562-5325 (Fax)	<a href="http://www.eetimes.com">http://www.eetimes.com</a>
Evaluation Engineering	Nelson Publishing	2500 Tamiami Trail North Nokomis, FL 34275	941-966-9521	<a href="http://evaluationengineering.com">http://evaluationengineering.com</a>
Passive Component	The Paumanok Group	132 Preston Exec. Dr. Cary NC 27513	919-468-0384	<a href="http://www.paumanokgroup.com/">http://www.paumanokgroup.com/</a>
Test & Measurement World	Reed Business Info. (Formerly Cahners)	275 Washington Street Newton MA 02458-1630	617-558-4671	<a href="http://www.e-insite.net/tmworld">http://www.e-insite.net/tmworld</a>
<b>Resources</b>				
The Capacitor Source	FaradNet	Knoxville, TN 37922	865-966-8958	<a href="http://www.faradnet.com">http://www.faradnet.com</a>
<b>Product Sites</b>				
Electronics	GlobalSpec Inc	350 Jordan Road Troy, NY 12180	518-880-0200	<a href="http://www.globalspec.com">http://www.globalspec.com</a>
Electronics	ChipCenter			<a href="http://www.chipcenter.com">http://www.chipcenter.com</a>

# Typical Measurement Parameters for a Variety of Components and Materials\*\*

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 <sub>p</sub>
"	Low-valued (rf)	1k - 1MHz	low	Series	L, Q, R <sub>s</sub>
Resistors	Low values	DC - 1kHz	varies	Series	R, Q, L
"	High values	DC - 100Hz	varies	Parallel	R, Q, C <sub>p</sub>
Materials	Insulators	DC, 1k, 1M	1, HV DC	Parallel	C, D, R, G, dielectric const, K
"	Semiconductors	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 & Transformers	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, $\theta$
Filters	Impedance	as required	any	Series/parallel	R, L, C, Q, G, Z, G, Y, $\theta$
Transducers		as required	any	Series/ parallel	Z, C, L, R, $\theta$
Sensors		as required	any	Series/ parallel	all

\*\* Partial Listing, Check Standard and Governing/Certifying Agency for specific requirements.

# Impedance Terms and Equations\*

Parameter	Quantity	Unit Symbol	Formula
Z	Impedance	ohm, $\Omega$	$Z = R_s + jX_s = \frac{1}{Y} =  Z  e^{jq}$
Z	Magnitude of Z	ohm, $\Omega$	$ Z  = \sqrt{R_s^2 + X_s^2} = \frac{1}{ Y }$
R <sub>s</sub> or ESR	Resistance, Real part of Z	ohm, $\Omega$	$R_s = \frac{G_p}{G_p^2 + B_p^2} = \frac{R_p}{1+Q^2}$
X <sub>s</sub>	Reactance, Imaginary part of Z	ohm, $\Omega$	$X_s = -\frac{B_p}{G_p^2 + B_p^2}$
Y	Admittance	siemen, S	$Y = G_p + jB_p = \frac{1}{Z} =  Y  e^{jf}$
Y	Magnitude of Y	siemen, S (was mho)	$ Y  = \sqrt{G_p^2 + B_p^2} = \frac{1}{ Z }$
G <sub>p</sub>	Real part of Y	siemen, S	$G_p = \frac{R_s}{R_s^2 + X_s^2}$
B <sub>p</sub>	Susceptance	siemen, S	$B_p = -\frac{X_s}{R_s^2 + X_s^2}$
C <sub>s</sub>	Series capacitance	farad, F	$C_s = -\frac{1}{\omega X_s} = C_p(1+D^2)$
C <sub>p</sub>	Parallel capacitance	farad, F	$C_p = \frac{B}{\omega} = \frac{C_s}{1+D^2}$
L <sub>s</sub>	Series inductance	henry, H	$L_s = \frac{X}{\omega} = L_p \frac{Q^2}{1+Q^2}$
L <sub>p</sub>	Parallel inductance	henry, H	$L_p = -\frac{1}{\omega B_p} = L_s(1+\frac{1}{Q^2})$
R <sub>p</sub>	Parallel resistance	ohm, $\Omega$	$R_p = \frac{1}{G_p} = R_s(1+Q^2)$
Q	Quality factor	none	$Q = -\frac{1}{D} = \frac{X_s}{R_s} = \frac{B_p}{G_p} = \tan q$
D, DF or tan $\delta$	Dissipation factor	none	$D = -\frac{1}{Q} = \frac{R_s}{X_s} = \frac{G_p}{B_p} = \tan(90^\circ - q) = \tan d$
$\theta$	Phase angle of Z	degree or radian	$q = -f$
$\phi$	Phase angle of Y	degree or radian	$f = -q$

**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 (R<sub>p</sub>) is sometimes used but parallel X (X<sub>p</sub>) is rarely used and series G (G<sub>s</sub>) and series B (B<sub>s</sub>) 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 (C<sub>p</sub> is common, L<sub>p</sub> 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  $\delta$  is used by some (especially in Europe) instead of D. tan  $\delta$  = D.

# LCR Selection Guide

Feature	1659	1689/89M	1692	1693	1715 CE	1730 CE
Accuracy (+/-)	0.1% LCR 0.0005 DQ	0.02% LCR 0.0001 DQ	0.05% LCR 0.0003 DQ	0.02% LCR 0.0001 DQ	0.2% LCR 0.002 DQ	0.1% LCR 0.0001 DQ
Test Frequency	100, 120, 1k, 10kHz	12Hz – 100kHz	100, 120, 1k, 10k & 100k Hz	12Hz – 200kHz	100, 120, 1k, 10kHz	100, 120, 1k, 10k, 20k, 50k & 100k Hz
Test Voltage	0.3V	5mV – 1.275V	0.3V and 1.0V	5mV – 1.275V	0.25V and 1.0V	10mV – 1.0V
Monitor V/I DUT	No	No	No	No	No	Yes
Measured Parameters	L, C, R, D, Q	L, C, R, D, Q	L, C, R, D, Q	L, C, R, Z, D, Q, $\theta$ , Y, G, X	L, C, R, Z, D, Q, $\theta$ , X	L, C, R, Z, D, Q, $\theta$ , X, ESR
Measurement Range	.00001mH-999999H .00001pF-99999mF .00001 $\Omega$ -99999M $\Omega$ .0001-9999	.00001mH-999999H .00001pF-99999uF .00001 $\Omega$ -99999k $\Omega$ 1ppm-9999	.00001mH-999999H .00001pF-99999mF .00001 $\Omega$ -99999M $\Omega$ .0001-9999	.00001mH-999999H .00001pF-99999uF .00001 $\Omega$ -99999k $\Omega$ 1ppm-9999 .00001° - 180° .00001uS-99999S	0.01uH-9.999kH 0.01pF-99.999mF 0.1m $\Omega$ -99.99M $\Omega$ 0.0001-9999 -180.00° - +180.00°	0.001uH-99.999kH 0.001pF-9.9999F 0.01m $\Omega$ -99.99M $\Omega$ 0.0001-9999 -180.00° - +180.00°
Measurement Speed	2, 4, or 8 meas/sec	Up to 50 meas/sec	2, 4, or 8 meas/sec	Up to 50 meas/sec	Up to 25 meas/sec	Up to 62 meas/sec
Display	Full 5 + 4 digits, Bin #	Full 5 + 4 digits, Bin #, $\Delta$ , $\Delta\%$	Full 5 + 4 digits, Bin #, $\Delta$ , $\Delta\%$	Full 5 + 4 digits, Bin #, $\Delta$ , $\Delta\%$	Full 5 + 4 digits, Bin #, $\Delta$ , $\Delta\%$	Full 5 digit (pri/sec) $\Delta$ , $\Delta\%$ , P/F, Bin#
Plot: F, V, I	No	No	No	No	No	No
Sequence	No	No	No	No	No	No
DC Bias Voltage	2V INT 0 - 60V EXT	2V INT 0 - 60V EXT	2V INT 0 - 60V EXT	2V INT 0 - 60V EXT	No No	0-5V INT with R <sub>BIAS</sub> 0 - 5V EXT
Test Connection	Built-In Kelvin plus Optional fixtures	Built-In Kelvin plus Optional fixtures	Built-In Kelvin plus Optional fixtures	Built-In Kelvin plus Optional fixtures	Kelvin Clips plus Optional fixtures	Kelvin Clips plus Optional fixtures
Auto Parameters	Yes	Yes	Yes	Yes	No	No
Auto Range	Yes	Yes	Yes	Yes	Yes	Yes
Binning	Yes (10)	Yes (15)	Yes (10)	Yes (15)	Yes (8)	Yes (8)
Bin Sum	No	Yes	No	Yes	Yes	Yes
Averaging	Yes (1 or 10)	Yes (1 – 256)	Yes (1 – 10)	Yes (1 – 256)	No	Yes (1-256)
Median Mode	No	Yes	No	Yes	No	No
Offset / Zero	Yes	Yes	Yes	Yes	Yes	Yes
Calibration	Optional Cal Kit	Optional Cal Kit	Optional Cal Kit	Optional Cal Kit	No	No
Save Setup	Yes	Yes	Yes	Yes	Yes	Yes (50)
Floppy Drive	No	No	No	No	No	No
Self Diagnostics	Yes	Yes	Yes	Yes	No	No
RS232	No	No	No	No	Yes	No
IEEE-488	Option	Option	Option	Option	Option	Yes
Handler Port	Option	Option	Option	Option	Option	Yes
Constant V	No	Yes	Yes	Yes	No	No
Constant I	No	No	No	Yes	No	No
Source	25, 400, 6.4k, 100k (Range dependent)	25, 400, 6.4k, 100k (Range dependent)	25, 400, 6.4k, 100k (Range dependent)	25, 400, 6.4k, 100k (Range dependent)	25, 100, 1k, 10k, 100k (DUT dependent)	100/25, 100, 25, 10 (Constant current)
Impedance ( $\Omega$ )						
Delta % ( $\Delta$ %)	No	Yes	Yes	Yes	Yes	Yes
Delta LCR	No	Yes	Yes	Yes	Yes	Yes
D & Q in ppm	No	Yes	No	Yes	No	No
Ratio Display	No	Yes	No	Yes	No	No
Program Delay	No	Yes	No	Yes	Yes	Yes (0-10s)

# LCR Selection Guide

Feature	1910 CE	1920 CE	7400 CE	7600 CE
Accuracy (+/-)	0.1% LCR 0.001 DQ 0.18°	0.1% LCR 0.001 DQ 0.18°	0.05% LCR 0.0005 DQ 0.18° AutoAcc™ 10Hz – 500kHz	0.05% LCR 0.0005 DQ 0.18° AutoAcc™ 10Hz – 2MHz
Test Frequency	20Hz – 1MHz	20Hz – 1MHz	20mV – 5.0V	20mV – 5.0V
Test Voltage	20mV – 1.0V	20mV – 1.0V	250uA – 100mA	250uA – 100mA
Test Current	No	No	No	No
Monitor V/I DUT	Yes	Yes	No	No
Measured Parameters	L, C, R, Z, D, Q, $\theta$ , Y, G, B, ESR, DCR	L, C, R, Z, D, Q, $\theta$ , Y, G, B, ESR, DCR	L, C, R, Z, D, Q, $\theta$ , Y, G, B	L, C, R, Z, D, Q, $\theta$ , Y, G, B
Measurement Range	0.001nH-99.999H 0.01pF-9.9999F 0.0001m $\Omega$ -99.999M $\Omega$ 0.00001-99.999 D 0.00000-9999.9 Q -180.000° - 179.99° 10nS-9999.9S 0.1m $\Omega$ -100k $\Omega$ DCR	0.001nH-99.999H 0.01pF-9.9999F 0.0001m $\Omega$ -99.999M $\Omega$ 0.00001-99.999 D 0.00000-9999.9 Q -180.000° - 179.99° 10nS-9999.9S 0.1m $\Omega$ -100k $\Omega$ DCR	0.001nH-99.9999H 0.01fF-9.9999F 0.0001m $\Omega$ -99.9999M $\Omega$ .1ppm-99.9999 D .1ppm-999999.9 Q -180.000° - 180° 0.01uS-9.999999MS	0.001nH-99.9999H 0.01fF-9.9999F 0.0001m $\Omega$ -99.9999M $\Omega$ .1ppm-99.9999 D .1ppm-999999.9 Q -180.000° - 180° 0.01uS-9.999999MS
Measurement Speed	Up to 40 meas/sec	Up to 40 meas/sec	Up to 40 meas/sec	25 meas/sec
Display	Full 5 digit (pri/sec) Engineering/Scientific $\Delta$ , $\Delta$ %, Pass/Fail Blank (No display)	Full 5 digit (pri/sec) Engineering/Scientific $\Delta$ , $\Delta$ %, Pass/Fail Blank (No display)	Full 7 digit (pri/sec), Bin #, Bin Sum, $\Delta$ , $\Delta$ %, Pass/Fail Blank (No display)	Full 7 digit (pri/sec), Bin #, Bin Sum, $\Delta$ , $\Delta$ %, Pass/Fail Blank (No display)
Plot: F, V, I	No	No	Yes	Yes
Sequence	Yes	Yes	Yes	Yes
DC Bias Voltage	No	0 - 2V INT	0 - 2V INT 0 - 200V EXT 0 - 500V EXT 7400A	2V INT 0 - 200V EXT 0 - 500V EXT 7600A
DC Bias Current	0 – 1.0A INT 0 – 20.0A EXT (1320)	No	No	No
Test Connection	4-BNC Kelvin plus Optional fixtures	4-BNC Kelvin plus Optional fixtures	4-BNC Guarded plus Optional fixtures	4-BNC Guarded plus Optional fixtures
Auto Parameters	Yes	Yes	Option	Option
Auto Range	Yes	Yes	Yes	Yes
Binning	No	No	Yes (15)	Yes (15)
Bin Sum	No	No	Yes	Yes
Averaging	Yes (1 – 1000)	Yes (1 – 1000)	Yes (1 – 1000)	Yes (1 – 1000)
Median Mode	Value of last 3 msmt	Value of last 3 msmt	Yes	Yes
Offset / Zero	Yes	Yes	Yes	Yes
Calibration	Built-In Auto Cal	Built-In Auto Cal	Built-In Auto Cal	Built-In Auto Cal
Save Setup	Yes	Yes	Yes	Yes
Floppy Drive	No	No	Yes	Yes
Self Diagnostics	Yes	Yes	Yes	Yes
RS232	Yes	Yes	Yes	Yes
IEEE-488	Yes	Yes	Yes	Yes
Handler Port	Yes	Yes	Yes	Yes
Printer Port	No	No	Yes	Yes
Constant Voltage	Yes	Yes	Yes	Yes
Constant Current	No	No	Yes	Yes
Source Impedance	5, 25, 50, 100 $\Omega$	5, 25, 50, 100 $\Omega$	25, 400, 6.4k, 100k $\Omega$ (Range dependent)	25, 400, 6.4k, 100k $\Omega$ (Range dependent)
Delta % ( $\Delta$ %)	Yes	Yes	Yes	Yes
Delta LCR	Yes	Yes	Yes	Yes
D & Q in ppm	Yes	Yes	Yes	Yes
Ratio Display	No	No	No	No
Program Delay	Yes (0 – 1000ms)	Yes (0 – 1000ms)	Yes (0 – 1000ms)	Yes (0 – 1000ms)

# LCR Accessory Selection Guide

Accessory		Instrument									
Part #	Description	1659	1689	1692	1693	1715	1730	1910	1920	7400	7600
1320-06	36-pin Interconnect Cable (7000)									x	x
1320-07	37-pin Interconnect Cable (1910)							x	x		
150261	7600 Instruction Manual										x
150262	7400 Instruction Manual									x	
150491	1910 Instruction Manual							x			
150566	1920 Instruction Manual								x		
150683	1730 Instruction Manual						x				
150710	1715 Instruction Manual					x					
1657-5995	Axial Lead Test Clips (4)	x	x	x							
1657-9600	Extender Cable (3') A/R to Banana	x	x	x							
1658-9620	IEEE-Handler Interface	x	x	x	x						
1659-0120	1659 Instruction Manual	x									
1689-0120	1689 & 89M Instruction Manual		x								
1689-9600	Remote Test Fixture	x*	x*	x*	x						
1689-9601	BNC Adapter Box	x	x	x							
1689-9602	BNC/BNC Extender Cable (1 meter)	x*	x*	x*	x						
1689-9604	Cal Kit: 1659, 89, 89M, 92 & 93	x	x	x	x						
1689-9605	Remote Fixture Strt & Go/NoGo LEDs	x*	x*	x*	x*						
1689-9611	Rack Mount Kit: 1689M & 1693		x (m)		x						
1689-9630	High Speed IEEE/Handler Interface		x (m)		x						
1692-0120	1692 Instruction Manual			x							
1693-0120	1693 Instruction Manual				x						
1700-01	Axial/Radial Component Test Fixture					x	x	x	x		
1700-02	Remote Component Test Fixture					x	x	x	x		
1700-03	Kelvin Clip Leads (1 meter)					x	x	x	x		
1700-04	BNC/Banana to Alligator Lead Set					x		x	x		
1700-05	Chip Component Tweezers					x		x	x		
1700-07	Kelvin Clip Leads (2 meters)					x		x	x		
1715-WZD	1715 Virtual Front Panel					x					
1900-WZD	1900 Virtual Front Panel							x	x		
2000-16	Rack Mount Flanges							x	x		
7000-00	Rack Mount Kit									x	x
7000-01	BNC Cable Set (1 meter)					x	x	x	x	x	x
7000-02	BNC Cable Set (2 meters)		x (m)		x	x	x	x	x	x	x
7000-03	Kelvin Clip Leads	x*	x*	x*	x					x	x
7000-04	Alligator Clip Leads									x	x
7000-05	Chip Component Tweezers	x*	x*	x*	x		x			x	x
7000-06	Axial/Radial Test Fixture									x	x
7000-07	Chip Component Test Fixture	x*	x*	x*	x	x	x	x	x	x	x
7000-08	High Voltage Test Fixture							x		x	x
7000-09	Calibration Kit									x	x
700171	IEEE/Handler Interface					x					

**For Reference Only**

\* This accessory requires the use of 1689-9601

(m) This accessory for use with the 1689M Digibridge

The 1658-9620 is required for the 1689-9605 Start & Go/No Go LEDs to illuminate correctly.

Refer to: <http://www.quadtech.com/products> for a complete list of accessories by product including descriptions, images and price information.

# Application Note Directory

# QuadTech Application Notes

Contained herein is a list of QuadTech application notes available for download in Adobe PDF format. To access the application notes visit: <http://www.quadtech.com/resources> and click on the Application Note link.

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# Glossary

**AC**

Alternating current, an electric current that has one polarity during part of the cycle and the opposing polarity during the other part 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 Df.

**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 impedance of the DUT. As a general rule this means 1VAC RMS signal level, 1kHz frequency, high accuracy which equates to 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**

Abbreviated as C (as in LCR). A capacitor is a passive component comprised of two conductors separated by a dielectric. A capacitor stores charge, blocks DC flow and allows AC flow based on frequency and capacitor design.

**Capacitance**

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**

Measurement of the actual AC resistance of a capacitor. How effective a capacitor is in allowing AC to flow depends upon its capacitance and frequency.

$$X_c = 1/2\pi fC.$$

**Clearance**

Clearance is 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 amount of time an instrument waits before performing a task.

**Dielectric**

A material which is an electric insulator or in which an electric field can be sustained with a minimum dissipation of power.

**Dielectric Constant**

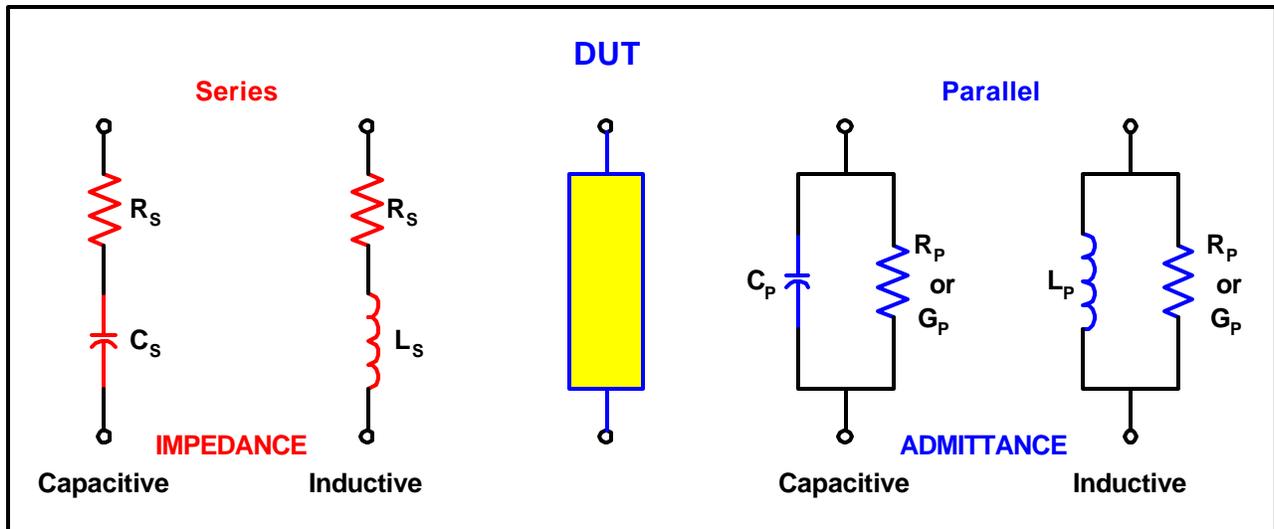
Abbreviate K, relative dielectric constant. The dielectric constant of a material is the ratio of the capacitance of a capacitor filled with a given dielectric to that same capacitor having only a vacuum as a dielectric.

**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.

**DUT**

Device Under Test - the product being tested.



Equivalent Circuit

**Dwell Time**

The amount of time the DUT is allowed to stabilize at the test voltage before measurements are performed.

**Electric Current**

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**

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**

An acronym for 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**

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**

An acronym for Institute of Electrical and Electronic Engineers, a professional association of 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

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.

Impedance (Z) is a vector summation of resistance (R) and reactance (X).

Capacitors: Reactance =  $X_C = 1/j\omega C$

Inductors: Reactance =  $X_L = j\omega L$

Resistors: Resistance = R

Impedance =  $Z = \text{square root}(X^2 + R^2)$

## Inductor

Abbreviated L (as in LCR). An inductor is a coil of wire. It is used to create electromagnetic induction in a circuit.

## Inductance

The property of a coil to oppose any change in current through it. If the turns (coils) of the wire are stretched out, the field intensity will be less and the inductance will be less. Unit of measure is the Henry (H).

## Inductive Reactance

A measure of how much the counter electro-magnetic force (emf) of the 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 configuration 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

Acronym for 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. For AC circuits, Current = Voltage/Impedance. Stated conversely, Voltage = Current x Resistance (DC) or Current x Impedance (AC). The difference between the dc resistance and ac impedance is that ac circuits must deal with phase and time relationships and dc circuits do not.

## Ohms (W)

The unit of measure 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 characterized of the device under test. The secondary parameter (D, Q,  $\theta$ ) is the second property characterized of the device under test.

**Permittivity**

Abbreviated  $\epsilon$ . The dielectric constant multiplied by the dielectric constant of empty space ( $\epsilon_0$ ), where the permittivity of empty space ( $\epsilon_0$ ) is a constant in Coulomb's law, equal to a value of 1 in centimeter-gram-second units and to  $8.854 \times 10^{-12}$  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	$10^{15}$	Peta	P
100000000000000	$10^{12}$	Tera	T
1000000000	$10^9$	Giga	G
1000000	$10^6$	Mega	M
1000	$10^3$	Kilo	k
0.001	$10^{-3}$	milli	m
0.000001	$10^{-6}$	micro	$\mu$
0.000000001	$10^{-9}$	nano	n
0.0000000000001	$10^{-12}$	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.

**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  $90^\circ$  out of phase with the "real" or in phase component. Reactive components are associated with capacitive or inductive circuits.

**Real**

The component of an ac 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 fixturing where the DUT being tested is removed from the fixture and then inserted again.

**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**

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 ( $\Omega$ ).

**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**

The Standards Council of Canada, an agency of the Canadian Government analogous to OSHA in the United States.

**Speed**

The rate at which the instrument makes a measurement in measurements per second. Speed is inversely proportional to accuracy.

**Spikes**

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 ohms, DUT is 25 ohms, 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 on the handler.

**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**

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).  $Z = R + jX$

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