Chroma
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Application Note

Chroma Systems Solutions, Inc.

LCR Measurement Primer

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LCR Meters

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Title: # LCR Measurement Primer

Product Family: **11021 LCR Meter, 11021-L LCR Meter, 11022 LCR Meter, 11025 LCR Meter, 11050 HF LCR Meter**

Table of Contents

Preface

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

What is Impedance?

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

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

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

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

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

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

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

Phase Shift

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

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

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

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

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

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

$\omega = 2\pi f$

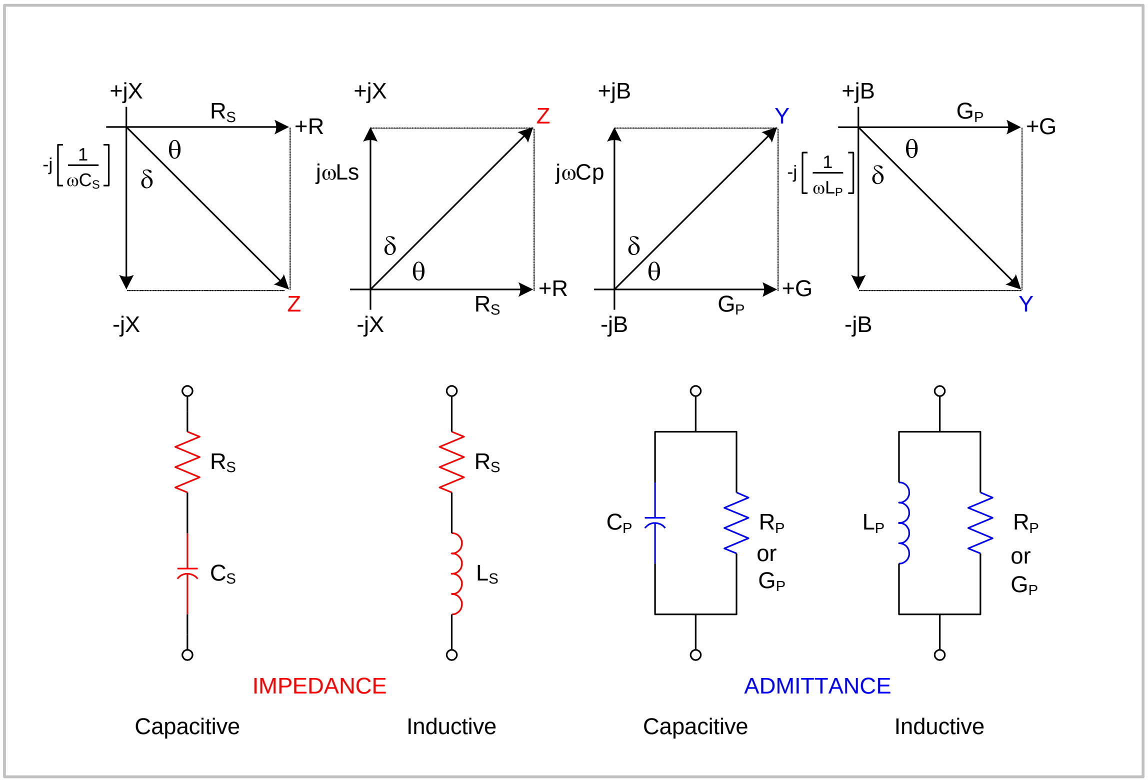


Figure 1. A Set of Vector Diagrams

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

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

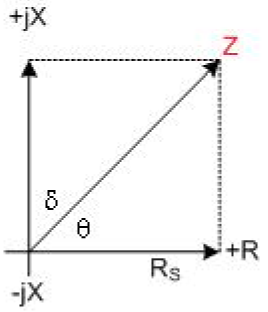
Series vs. Parallel Equivalencies

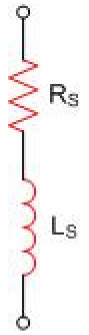
Which should be measured, series or parallel parameters? It depends on the purpose of the measurement. For incoming inspection and production measurements on passive components the series values is usually specified in EIA and MIL standards. These standards also specify test frequencies and other test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

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

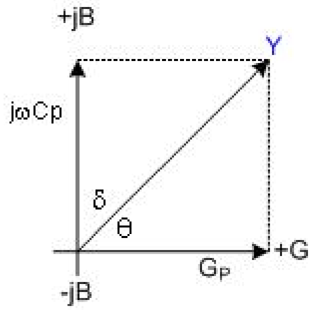
Other cases where parallel measurements are preferred are when measuring very low values of capacitance, when making measurements on dielectric and magnetic materials, and when trying to determine the separate values of two components in parallel. If the D of a capacitor is less than .01, it doesn't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

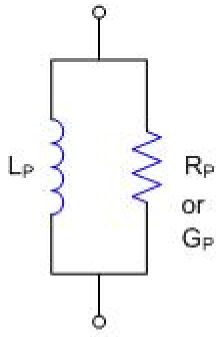
An equivalent circuit for this impedance would put R_S and X_S in series, hence the subscript “S”.





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





For a complete list of Impedance Terms & Equations, please see Page 38.

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

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

Reactance comes in two types, inductive and capacitive. The reactance of an inductive element is L, where L is its inductance and = 2πf (where f = frequency). The reactance of a capacitive element is negative, -1/ C, where C is its capacitance. The negative sign occurs because the impedance of a pure capacitor is 1/j C and 1/j = -j.

Because the impedance of two devices in series is the sum of their separate impedances, consider impedance as the series combination of an ideal resistor and an ideal capacitor or inductor. This is the series equivalent circuit of impedance comprising an equivalent series resistance and an equivalent series capacitance or inductance. Using the subscript s for series, we have:

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

For a network having many components, the element values of the equivalent circuit change with the frequency. This is also true of the values of both the inductive and the capacitive elements of the equivalent circuit of a single, actual component (although the changes are usually very small).

Impedance is represented, at any specific frequency, by an equivalent circuit. The values of these elements or parameters depend on which representation is used, series or parallel, except when the impedance is purely resistive or purely reactive. In such cases only one element is necessary and the series or parallel values are the same.

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

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

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

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

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

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

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

$$= \quad Gp + jBp$$

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

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

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

Connection Methods

Connection to the device under test (DUT) determines most accurately the value of the DUT's impedance. 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

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

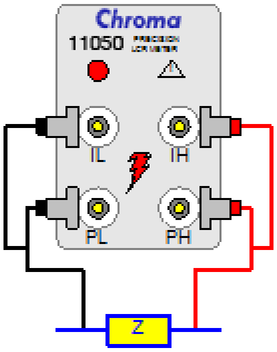


Figure 2.
Two-Terminal Measurement

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

The use of multiple connections can reduce or remove impedance measurement errors caused by series impedance in the connections or shunt impedance across the unknown.

Four-Terminal Measurements

First let's jump into four-terminal measurements, which are simpler to explain and more commonly used than a three-terminal measurement. With a second pair of terminals available, one can measure voltage across the device with one pair and apply current to the device with the other pair. This simple improvement of independent leads for voltage and current effectively removes the series inductance and resistance error factor (including contact resistance) and the stray capacitance factor discussed with two-terminal measurements.

Accuracy for the lower impedance measurement range is now substantially improved down to 1Ω and below. There will be some mutual inductance between the current leads and voltmeter leads which will introduce some error, but much of this is eliminated by using shielded coaxial cabling. The most famous use of the four-terminal connection is the Kelvin Bridge, which has been widely used for precision DC resistance measurements.

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

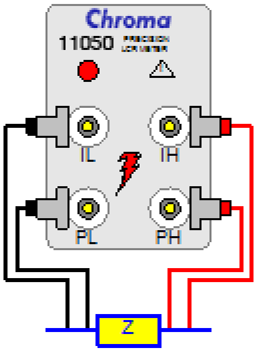


Figure 3.
Four-Terminal Measurement

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.

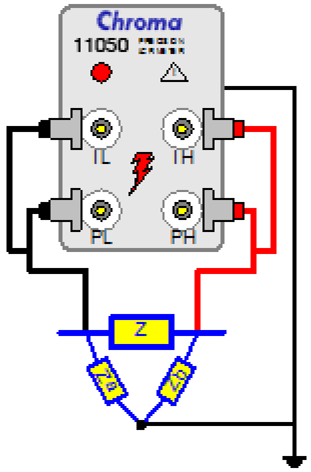


Figure 4. Three Terminal Kelvin

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

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

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

Equation 6:

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

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

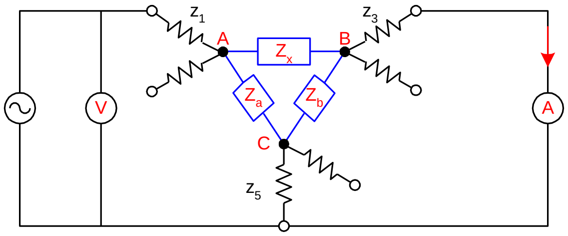


Figure 5. Three-Terminal Guarded using Delta Impedance Configuration

Measurements of Impedance

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

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

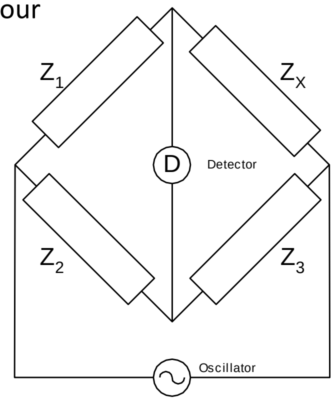


Figure 6. Nulling Bridge

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

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

Most recently instruments have been developed which employ elaborate software-driven control and signal processing techniques. For example, the Chroma 11050 HF LCR Meter uses a principle of measurement which differs significantly from that employed by the traditional measuring instruments. In particular, the 11050 uses digital techniques for signal generation and detection. Both the voltage across the device under test (Zx) and the voltage across a reference resistor (Rs) are measured, which essentially carry the same current.

The voltage across Zx is Vx and the voltage across Rs is Vs. Both voltages are simultaneously sampled many times per cycle of the applied sine wave excitation. In the case of the 11050, there are four reference resistors. The one used for a particular measurement is the optimal resistor for the device under test, frequency, and amplitude of the applied AC signal. For both Vx and Vs a real and imaginary (in phase and quadrature) component are computed mathematically from the individual sample measurements.

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

Functions

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

Test Voltage

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

A source resistance (Rs, internal to the meter) is effectively connected in series with the AC output and there is a voltage drop across this resistor. When a test device is connected, the voltage applied to the device depends on the value of the source resistor (Rs) and the impedance value of the device.

Here are the factors of constant source impedance, where the programmed voltage is 1V but the voltage to the test device is 0.5V.

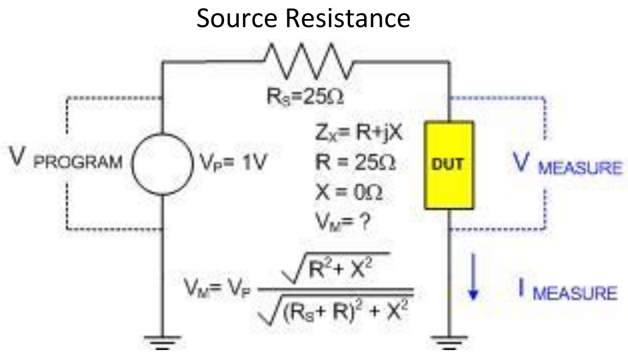


Figure 7. Source Impedance Factors

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

Ranging

In order to measure both low and high impedance values, the instrument must have several measurement ranges. Ranging is usually done automatically and selected depending on the impedance of the test device. Switching range resistors and the gain of detector circuits maintain the maximum signal level and the highest signal-to-noise ratio keep the measured impedance close to full scale for any given range.

Range holding, rather than auto ranging, is a feature sometimes used in specific applications. For example, when testing components of similar value, range holding reduces test time. Range holding is also effective when measuring components whose value falls within the overlap area of two adjacent ranges. In this case, auto range causes the instrument’s display to change, possibly confusing the operator.

Integration Time

When integration of analog signals occurs over more cycles of the test, the measurement time will be longer but more accurate. Measurement time is controlled by the operator, who selects a FAST or SLOW mode.

To improve repeatability (precision), try the Averaging mode, in which multiple measurements are made and the average of these calculated. This is a way of reducing noise, but does take time.

Median Mode

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

Computer Interface

Today's testers need a standard data communication interface to a host computer data processing or remote control. For an operation retrieving only pass/fail results, Programmable Logic Control (PLC) is often adequate, but for data logging it's a different story. The typical interface for this is the IEEE-488 general purpose interface bus or the RS-232 serial communication line.

These interfaces are necessary for process control in component manufacturing as well as in data archiving. For example, when testing 10% of components, the yield is fine when components test at 8% or 9%, but it does not take much of a shift for the yield to plummet. The whole idea of production monitoring is to reduce yield risks and correct the process quickly if needed. An LCR Meter with remote interface is standard in many test applications where data logging or remote control is common.

Compensating for Impedance in Fixtures and Cables

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

Compensation is a three-step process:

- Measuring the residual or “stray” capacitance between the test leads (in our illustrations, these are Kelvin test leads).
- Performing an Open/Short correction
- Performing a Load correction

Stray Capacitance

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

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

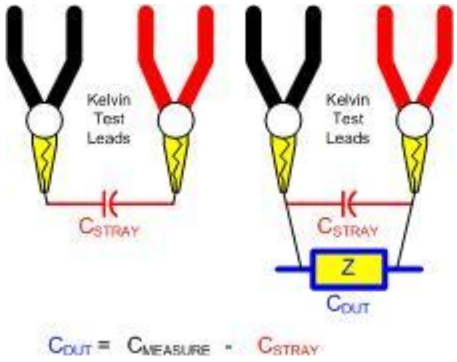


Figure 8. Stray Capacitance

Open/Short Correction

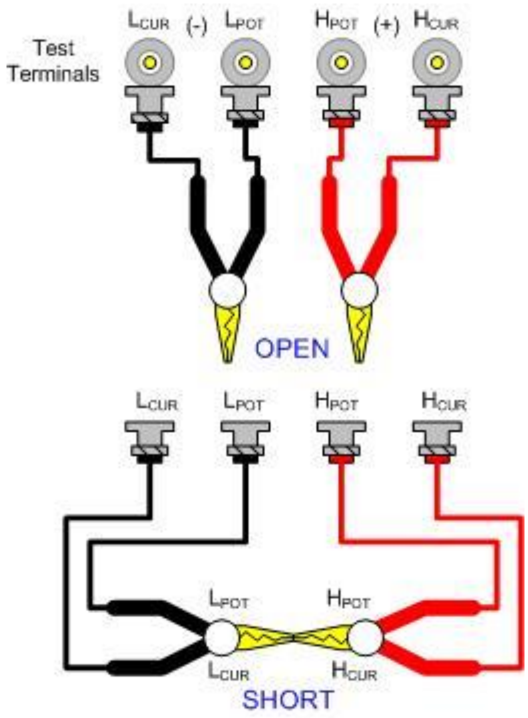


Figure 9. Open/Short

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

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

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

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

Load Correction

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

The appropriate load has the following properties:

- Impedance value is accurately known.
- Impedance value is close to the DUT's. (This ensures that the measuring instrument selects the same measurement range for both devices).
- Impedance value is stable under the measurement conditions.
- Physical properties allow using the same leads or fixture as the DUT.

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

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

Measurements of Capacitance

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

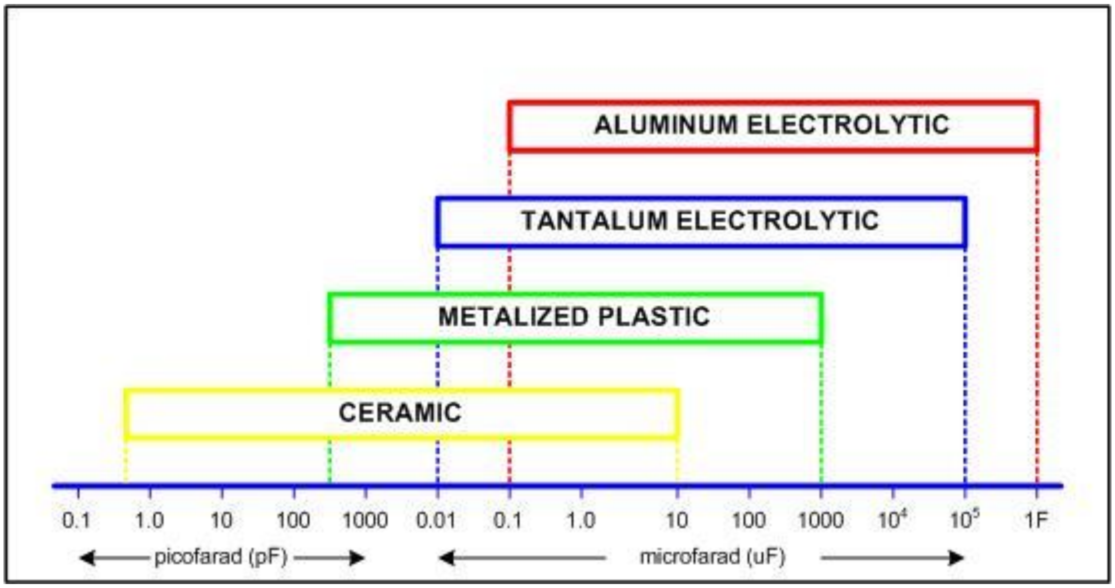


Figure 10. Dielectric Materials

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

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

ESR stands for equivalent series resistance, the same quantity that we call Rs in the above discussion. ESR is a measure of the loss in a capacitor and is related to D by:
ESR = Rs = D/ Cs(see Appendix A)

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

When the frequency is high or the capacitance is high, or both, the ESR often will approximate the actual series resistance because this resistance becomes the largest cause of loss under these conditions. However, ESR is always larger than this actual series resistance.

ESR is a measure of the total “lossiness” of a capacitor. It is larger than Ras because the actual series resistance is only one source of the total loss (usually a small part).

At any frequency, a measure of complex impedance gives two numbers, the real part and the imaginary part: Z = Rs + jXs. At that frequency, the impedance behaves like a series combination of an ideal resistance Rs and an ideal reactance Xs. If Xs is negative, the impedance is capacitive and the reactance can be replaced with capacitance as shown in equation 8.

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

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

ESR = Rs = Real part of Z

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

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

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

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

$$= Rs\omega C$$

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

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

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

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

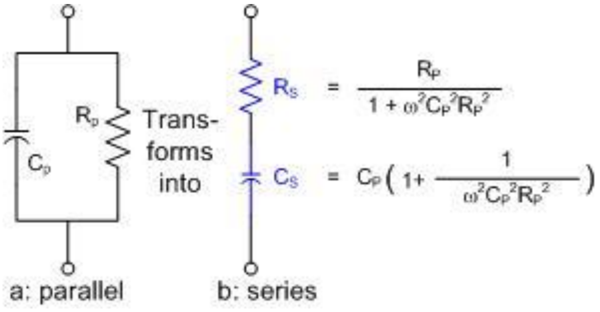


Figure 11. ESR

Series or Parallel

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

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

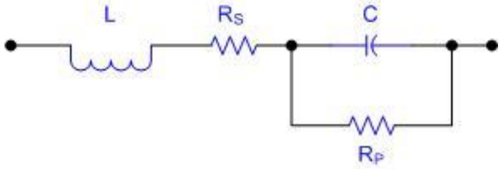


Figure 12. Equivalent Circuit for a Capacitor

Measuring a capacitor in series mode provides a different result than measuring in parallel mode. How they differ depends on Q (the ratio of energy stored to energy lost).

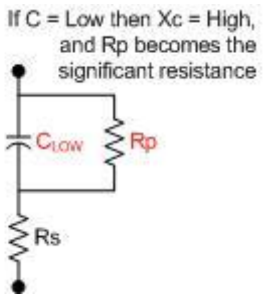


Figure 13.
Low Capacitance Equivalent Circuit

Regardless of Q, the capacitors measured value most closely represents its effective value when the more suitable equivalent circuit, series or parallel, is used. To determine which mode is best, consider the impedance magnitudes of the capacitive reactance, Rs and Rp. Reactance is inversely proportional to capacitance. In other words a small C yields large reactance, which means that the effect of parallel resistance (Rp) has a more significant effect than that of series resistance (Rs).

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

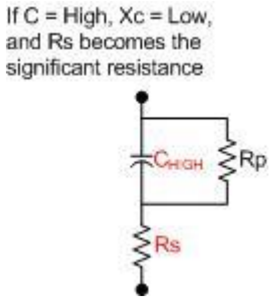


Figure 14.
High Capacitance Equivalent Circuit

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

- Above approximately 10 kΩ use parallel mode
- Below approximately 10Ω use series mode
- Between these values, follow manufacturer's recommendation
- Translated to a 1kHz test: Below 0.01 mF, use Cp mode; above 10 mF, use Cs mode; between these values use the manufacturer's recommendation.

Measuring Large and Small Values of Capacitance

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

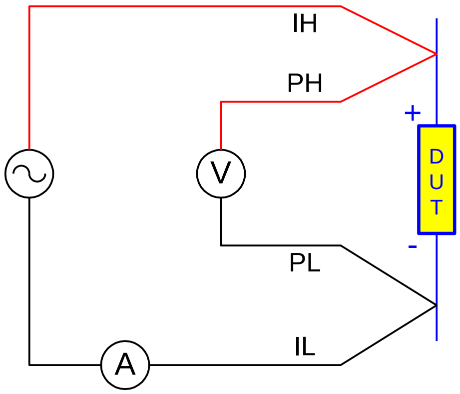


Figure 15. Diagram of Kelvin Connection

For the best of both worlds a four-terminal connection (often termed Kelvin), shown in figure 15, reduces the effects of lead impedance for large-value capacitors.

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

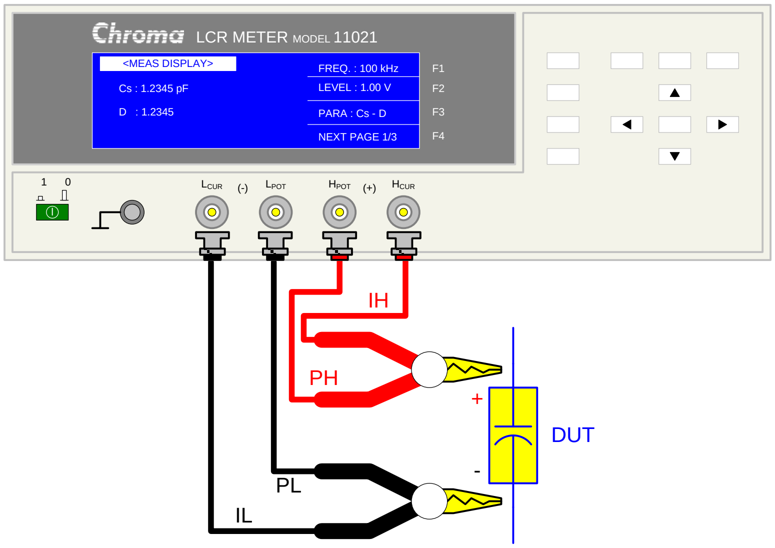


Figure 16. Functional Kelvin

Besides a four-terminal connection made as close as possible to the DUT, a further enhancement is an OPEN/SHORT compensation by the measuring instrument. The open/short compensation subtracts ("zeroes out") the effects of stray mutual inductance between test connections and lead inductance. (The effect of lead inductance increases the apparent value of the capacitance being measured.) Through OPEN/SHORT compensation, each residual parameter can be measured and the value of a DUT automatically corrected.

Aim toward consistency in techniques, instruments, and fixtures. This means using the manufacturer's recommended 4-terminal test leads (shielded coax) for the closest possible connection to the DUT. The OPEN/SHORT should be performed with a true open or short at the test terminals. For compensation to be effective, the open impedance should be 100 times more than the DUT impedance and the short impedance 100 times less than the DUT impedance. Of equal importance, when performing open/short zeroing, the leads must be positioned exactly as the device under test expects to see them.

Measurements of Inductance

SAFETY FIRST

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

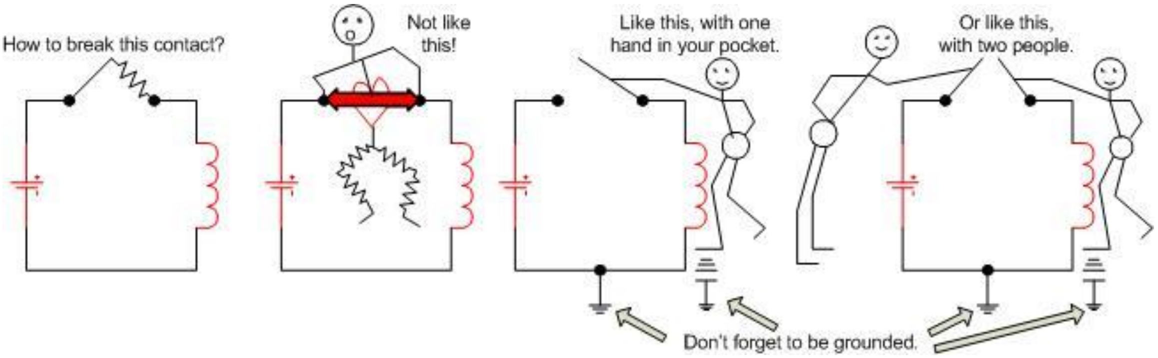


Figure 17. Safely Breaking Contact

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

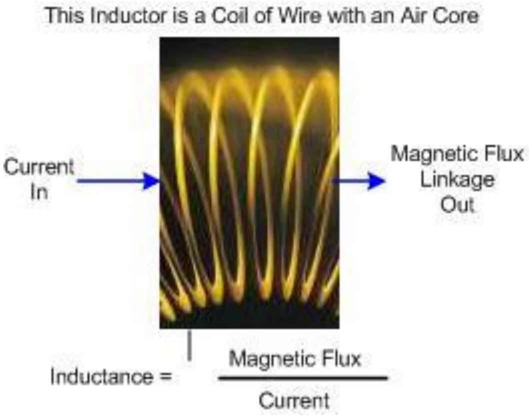


Figure 18. Inductor Defined

Series or Parallel

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

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.

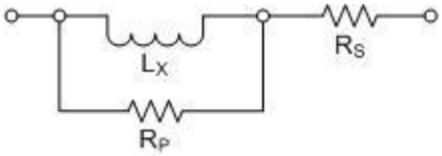


Figure 19. Inductor Circuit

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

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

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

Inductance Measurement Factors

Here are four factors for consideration in measuring actual inductors:

- DC Bias Current
- Constant Voltage (Voltage Leveling)
- Constant Source Impedance
- DC Resistance & Loss

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

DC Bias Current

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

Constant Voltage (Voltage leveling)

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

Constant Source Impedance

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

DC Resistance and Loss

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

Loss: Copper, Eddy Current, and Hysteretic

Three possible sources of loss in an inductor measurement are copper, eddy-current and hysteretic. They are dependent on frequency, signal level, core material and device heating.

As stated above, copper loss at low frequencies is equivalent to the DC resistance of the winding. Copper loss is inversely proportional to frequency. (As frequency increases, the copper loss decreases.) Copper loss is typically measured using an inductance analyzer that measures DC resistance rather than an AC signal.

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

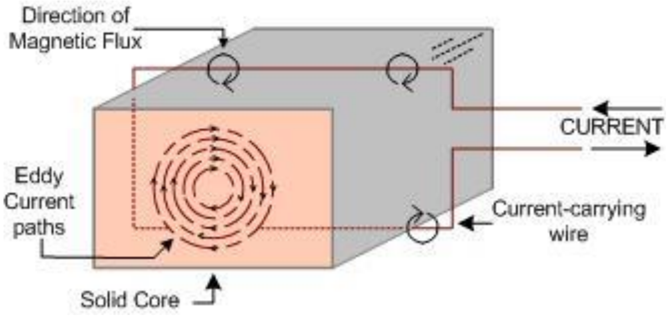


Figure 20. Eddy Currents

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

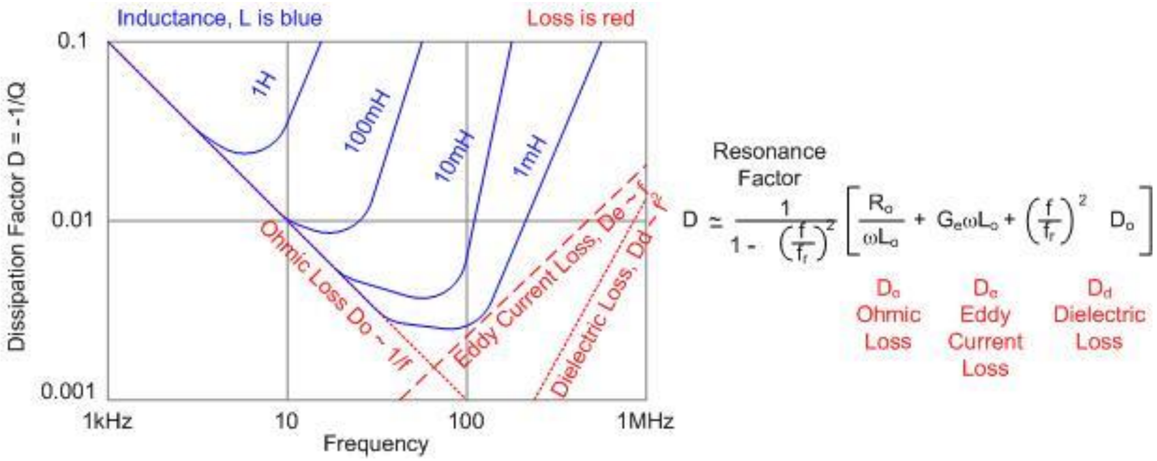


Figure 21. Dissipation Factor

Measurements of Resistance

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

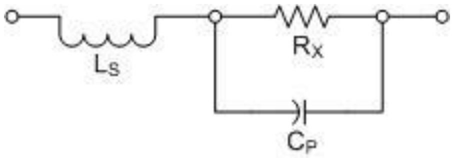


Figure 22. Resistor Circuit

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

Series or Parallel

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

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

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

Measurement of Solids and Liquids

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

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

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

and

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

The complex relative permittivity is:

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

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

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

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

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

where Ka is the dielectric constant of air:

$$K_a = 1.00053$$

if the air is dry and at normal atmospheric pressure.

Measurement Methods, Solids: The Contacting Electrode Method

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

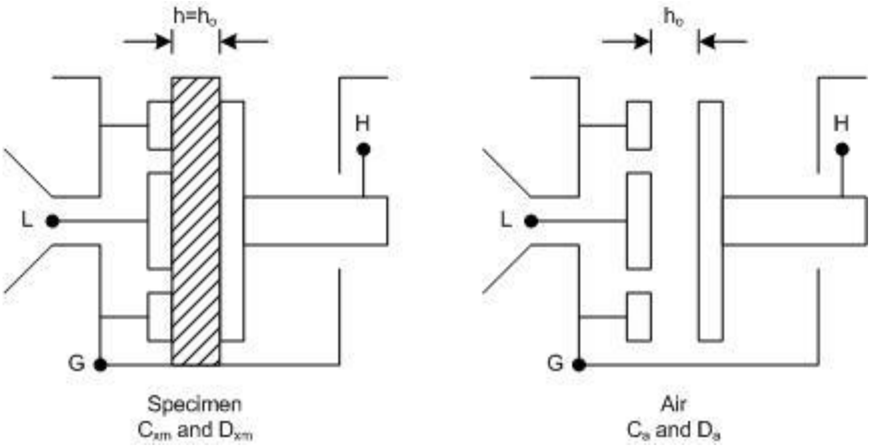


Figure 23. Contact Electrode

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

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

Calculate K_x and D_x of the sample from:

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

and

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

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

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

Air-Gap Method

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

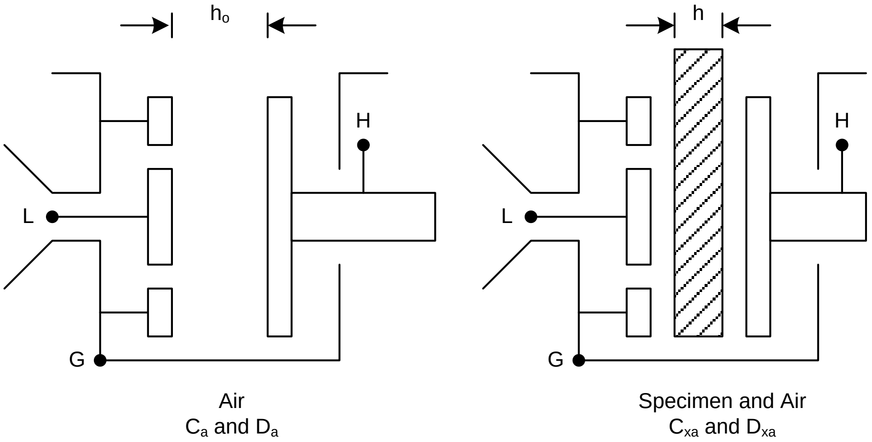


Figure 24. Air-Gap Method

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

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

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

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

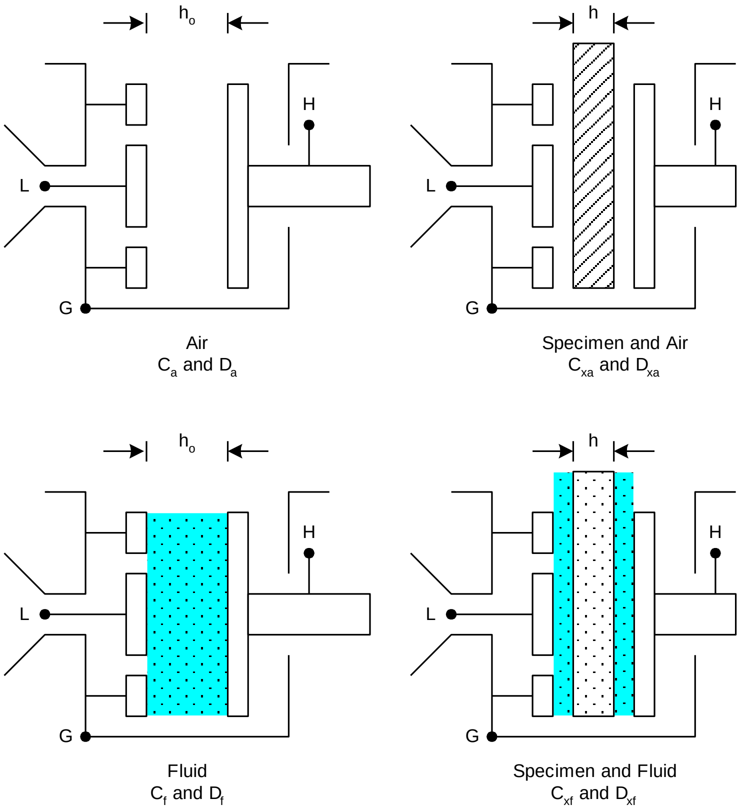
$$D = (D_{xa} - D_a)\left(\frac{C_a}{C_a - MC_{xa}}\right)$$

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

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

Two-Fluid Method

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



Air
C_a and D_a

Specimen and Air
C_{xa} and D_{xa}

Fluid
C_f and D_f

Specimen and Fluid
C_{xf} and D_{xf}

Figure 25. Two-Fluid Method

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

From these measurements calculate:

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

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

which is the ratio of the equivalent series capacitance of the sample to Ca.

If Dx is close to Dxf or larger use:

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

If Dx is very small, use:

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

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

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

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

Measurement Methods, Liquids

Measurements on liquids are simple—the only difficulty is with handling and cleanup.

Equivalent parallel capacitance and D of air (Ca and Da), is measured first and then that of the liquid (Cxm and Dxm)

Determine Kx and Dx:

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

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

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

What an LCR Meter Should Do

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

Test Frequency

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

Test Voltage

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

Accuracy/Speed

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

Measurement Parameters

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

Ranging

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

Averaging

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

Median Mode

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

Computer Interface

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

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

Display

An instrument with multiple displays provides measured results by application at the press of a button. Production environments may prefer a Pass/Fail or Bin Summary display. R&D Labs may need a deviation from nominal display. The 11050 series instruments have seven display modes: measured parameters, deviation from nominal, % deviation from nominal, Pass/Fail, Bin Summary, Bin Number and No Display.

Binning

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

Nested Limits

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

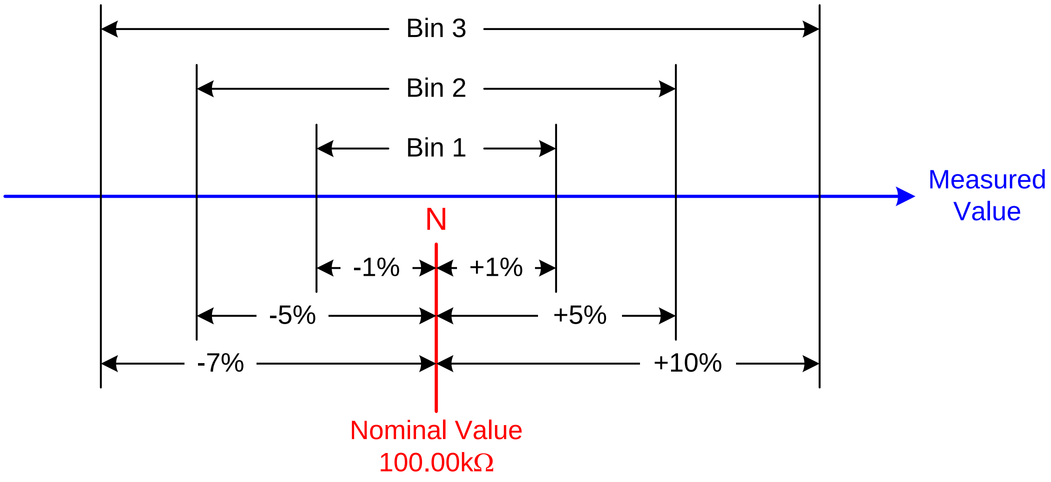


Figure 26. Nested Limits

Sequential Limits

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

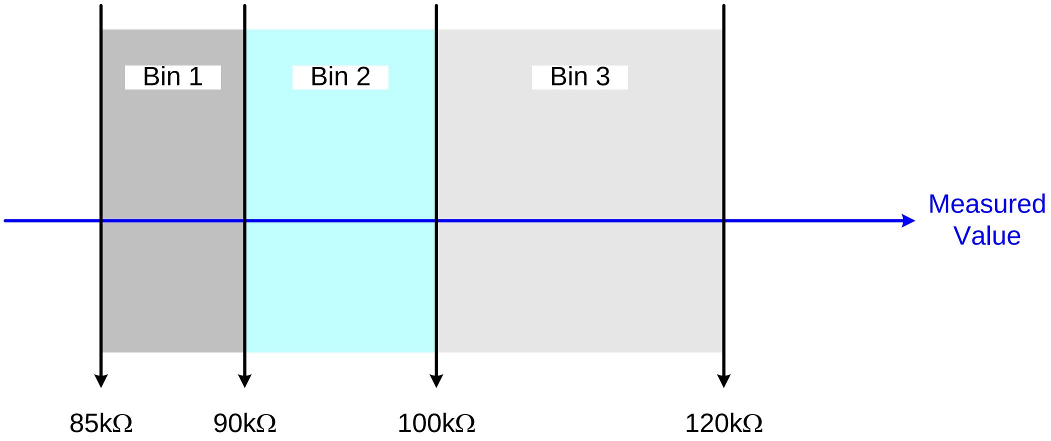


Figure 27. Sequential Limits

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 Chroma 11050 HF LCR 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).

Bias Voltage and Bias Current

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

Constant Source Impedance

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

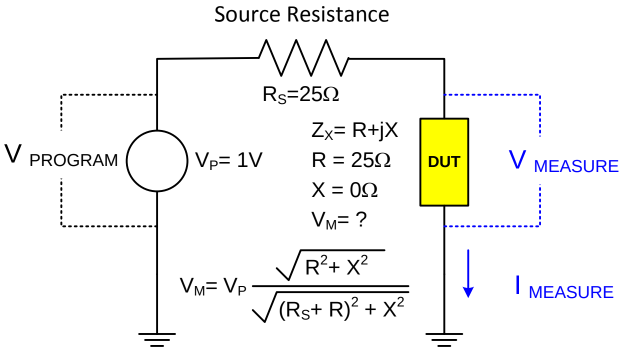


Figure 28. Constant Source Impedance

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.

Examples of High-Performance Testers

11021/11021-L LCR Meter

- Test Frequencies:
  100Hz, 120Hz, 1kHz and 10kHz (9.6kHz) (11021)
  1kHz, 10kHz, 40kHz, 50kHz (11021-L)
- Basic Accuracy: 0.1% (11021), 0.2% (11021-L)
- 0.1mO~99.99 MO measurement range, 4 1/2 digits resolution
- Lower harmonic-distortion affection
- Fast measurement speed (75ms)
- Standard RS-232 interface
- Optional GPIB & Handler interface
- Programmable trigger delay time is convenient for measurement timing adjustment in automatic production
- Bin-sorting function
- Comparator and pass/fail alarming beeper function
- Text mode 40x4 matrixes LCD display
- Friendly user interface
- Open/short zeroing
- On-line firmware refreshable (via RS-232)
- Input protection (1 Joule)

11022/11025 LCR Meter

- 0.1% basic accuracy
- Transformer test parameters (11025), Turns Ratio, DCR, Mutual Inductance
- 0Hz, 60Hz, 100Hz, 120Hz, 1kHz, 10kHz, 20kHz, 40kHz, 50kHz, 100kHz test frequencies
- 21ms measurement time (≥100Hz)
- Agilent 4263B LCR Meter commands compatible
- 4 different output resistance modes selectable for non-linear inductor and capacitor measuring
- High resolution in low impedance(0.01mO) and high accuracy 0.3% till 100mO range
- Adjustable DC bias current up to 200mA (constant 25O) (11025)
- 1320 Bias Current Source directly control capability
- 0.01mO ~ 99.99MO wide measurement range (4 1/2 digits)
- Dual frequency function (11022 option) for automatic production
- BIAS comparator function
- Comparator function and 8/99 bin-sorting function
- Pass/fail judge result for automatic production
- Handler interface trigger edge (rising/falling) programmable
- Test signal level monitor function

- Standard GPIB (IEEE-488) and handler interface, option RS 232 I/F
- Open/short zeroing, load correction
- LabView® Driver

11050 HF LCR Meter

- Test Parameters: L/C/R/Z/Y/DCR/Q/D/ θ
- Test Frequencies: 1kHz ~ 10MHz
- Test Level: 10mV ~ 5V
- Basic Accuracy: 0.1%
- 15ms fast speed measurement
- 3 kinds of output impedance modes
- Test signal monitoring function
- Compare & bin-sorting function
- Open/short zeroing & load correction functions
- Detached measurement & display unit design
- Standard Handler, RS-232C, USB storage & external bias current control interface
- Optional GPIB or LAN interfaces

Dedicated Function Test Instruments

In addition to passive component test instrumentation, Chroma manufactures milliohmmeters, megohmmeters, TEC Controllers and Dataloggers, AC and DC Sources, AC/DC Hipot Testers, and Electrical Safety Analyzers. View any product specification at http://www.chromausa.com.

Impedance Terms and Equations*

NOTES:

1. f = frequency in Hertz; j = square root (-1); ω = 2πf
2. R and X are equivalent series quantities unless otherwise defined. G and B are equivalent parallel quantities unless otherwise defined. Parallel R (Rp) is sometimes used but parallel X (Xp) is rarely used and series G (Gs) and series B (Bs) are very rarely used.
3. C and L each have two values, series and parallel. If no subscript is defined, series configuration is usually, but not necessarily, implied - especially for C (Cp is common, Lp is less often 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 δ is used by some (especially in Europe) instead of D. Tan δ = D.

Parameter	Quantity	Unit Symbol	Formula
Z	Impedance	ohm, Ω	$Z = R_S + jX_S = \frac{1}{Y} = \mid Z \mid \varepsilon^{j\theta}$
|Z|	Magnitude of Z	ohm, Ω	$\mid Z \mid = \sqrt{R_S^2 + X_S^2} = \frac{1}{\mid Y \mid}$
R_S or ESR	Resistance, Real part of Z	ohm, Ω	$R_S = \frac{G_P}{G_P^2 + B_P^2} = \frac{R_P}{1+Q^2}$
X_S	Reactance, Imaginary part of Z	ohm, Ω	$X_S = -\frac{B_P}{G_P^2 + B_P^2}$
Y	Admittance	siemen, S	$Y = G_P + jB_P = \frac{1}{Z} = \mid Y \mid \varepsilon^{j\phi}$
|Y|	Magnitude of Y	siemen, S (was mho)	$\mid Y \mid = \sqrt{G_P^2 + B_P^2} = \frac{1}{\mid Z \mid}$
G_P	Real part of Y	siemen, S	$G_P = \frac{R_S}{R_S^2 + X_S^2}$
B_P	Susceptance	siemen, S	$B_P = -\frac{X_S}{R_S^2 + X_S^2}$
C_S	Series capacitance	farad, F	$C_S = -\frac{1}{\omega X_S} = C_P(1+D^2)$
C_P	Parallel capacitance	farad, F	$C_P = \frac{B}{\omega} = \frac{C_S}{1+D^2}$
L_S	Series inductance	henry, H	$L_S = \frac{X}{\omega} = L_p \frac{Q^2}{1+Q^2}$
L_P	Parallel inductance	henry, H	$L_P = -\frac{1}{\omega B_P} = L_S(1+\frac{1}{Q^2})$
R_P	Parallel resistance	ohm, Ω	$R_P = \frac{1}{G_P} = R_S(1+Q^2)$

Q	Quality factor	none	$Q=-\frac{1}{D}=\frac{X_S}{R_S}=\frac{B_P}{G_P}=\tan\theta$
D or tan δ	Dissipation factor	none	$D=-\frac{1}{Q}=\frac{R_S}{X_S}=\frac{G_P}{B_P}=\tan(90^0-\theta)=\tan\delta$
θ	Phase angle of Z	degree or radian	$\theta=-\phi$
ϕ	Phase angle of Y	degree or radian	$\phi=-\theta$

NRTLs and Standards Organizations

NRTL stands for Nationally Recognized Testing Laboratories

- Underwriters Laboratories, Inc.

  333 Pfingsten Road Northbrook, Illinois 60062 USA

  Tel: 847-272-8800, http://www.ul.com

- American National Standards Institute

  25 West 43rd Street New York, NY 10036

  Tel: 212-642-4900, http://www.ansi.org

- British Standards Institution

  389 Chiswick High Road London W4 4AL, United Kingdom

  Tel: +44 845 086 9001, http://www.bsigroup.com/en-GB/

- CENELEC Comité Européen de Normalisation Electrotechnique

  Avenue Marnix 17, 4th Floor, B - 1000 Brussels, Belgium

  Tel: +32 2 519 68 71, http://www.cenelec.eu

- Canadian Standards Association

  178 Rexdale Blvd., Toronto, ON, Canada M9W 1R3

  Tel: 416-747-4000 or 800-463-6727, http://www.csagroup.org/

- VDE-Verband Deutscher Elektrotechniker

  Stressemannallee 15, 60596 Frankfurt am Main, Germany

  Tel: +49 69 6308-0, http://www.vde.com

- Japanese Standards Association

  Mita MT Bldg., 3-13-12 Mita, Minato-ku, Tokyo, 108-0073, Japan

  Tel: +81 3 4231 8503, http://www.jsa.or.jp

- IEC International Electrotechnical Commission

  3, rue de Varembé, PO Box 131, CH-1211 Geneva 20, Switzerland

Tel: +41 22 919 02 11, http://www.iec.ch

- Institute of Electrical and Electronic Engineers, Inc

  445 and 501 Hoes Ln, Piscataway NJ 08854-4141 USA

  Tel: 800-678-IEEE(4333) http://www.ieee.org

- NIST National Institute of Standards and Technology

  100 Bureau Dr., Stop 1070, Gaithersburg, MD 20899-1070

  Tel: 301-975-NIST(6478), http://www.nist.gov

- National Electrical Manufacturers Association

  1300 North 17th St. Suite 900, Arlington VA 22209

  Tel: 703-841-3200, http://www.nema.org

- ISO International Standards Organization

  1, ch. de la Voie-Creuse, CP 56, CH-1211 Geneva 20, Switzerland

  Tel: + 41 22 749 01 11, http://www.iso.org

- OSHA Region 1 Regional Office

  JFK Federal Building, Room E340 Boston, Massachusetts 02203

  Tel: 617-565-9860, http://www.osha.gov

- TÜV Rheinland of North America, Inc.

  1300 Massachusetts Avenue, Suite 103, Boxborough, MA 01719

  Tel: 203-426-0888 http://www.tuv.com/en/usa

Typical Measurement Parameters

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

LCR Selection Guide

Feature	11050 HF	11021/11021-L	11022/11025
Test Parameters	L, C, R, Z, Y, DCR, Q, D, θ	L, C, R, |Z|, Q, D, ESR, Xs, θ	**11022**: L,C, R, |Z|, Q, D, ESR, X,θ **11025**: L,C, R, |Z|, Q, D, ESR, X,θ, DCR4, M, Turns Ratio, L2, DCR2
Test Signal			
Test Frequency	1kHz ~ 10MHz	100, 120, 1k, 10kHz	50Hz, 60Hz, 100Hz, 120Hz, 1kHz, 10kHz, 20kHz, 40kHz, 50kHz, 100kHz
Test Level	≦1MHz : 10mV ~ 5V; ± [(10 + fm)% + 1mV] >1MHz : 10mV ~ 1V; ± [(10 + fm)% + 1mV] fm : test frequency [MHz]	**11021**: 0.25V / 1V , ±(10% + 3 mV) **11021-L**: 50mV/ 1V, ±10%+3mV	10 mV~1V , step 10 mV; ±(10% + 3 mV)
Output Impedance	100Ω, 25Ω, OFF	Varies as range resistors 25, 100, 1k, 10k, 100k	Constant 107X : 25Ω ; Constant 320X : 100Ω ; Constant 106X : 2Ω,for Z≧10Ω, 100mA (1V setting) for reactive load≦10Ω ; Constant 102X : 25Ω, for Z<1Ω, 100Ω for else
DC Bias Current (Freq. ≧ 1kHz)			**11025**: 50mA max. for Constant 100Ω, 200mA max for Constant 25Ω (AC level ≦ 100mV)
Measurement Display Range			
L	0.00001uH ~ 99.999MH	0.01µH ~ 9.999kH	0.001µH ~ 99.99k
L2			0.001µH ~ 99.99k
C	0.00001pF ~ 999.999F	0.01pF ~ 99.99mF	0.001pF ~ 1.9999F
R	0.01mΩ ~ 9999.99MΩ	0.1m. ~ 99.99MΩ	0.01mΩ ~99.99MΩ
X	0.01mΩ ~ 9999.99MΩ		
Z	0.01mΩ ~ 9999.99MΩ		
|Z|		0.1m. ~ 99.99MΩ	0.01mΩ ~99.99MΩ
DCR	0.01mΩ ~ 999.99MΩ		**11025**: 0.01mΩ~99.99MΩ
Q, D	0.00001 ~ 99999	0.1 ~ 9999.9	0.0001 ~ 9999
θ	-90.00° ~ 90.00°	-180.00˚~ +180.00˚	-180.00˚ ~ +180.00˚
M			0.001µH ~ 99.99k

Feature	**11050 HF**	**11021/11021-L**	**11022/11025**
Turns Ratio (Np:Ns)			**11025**: 0.9~999.99
Basic Accuracy			
Z	± 0.1%	**11021**: ±0.1% **11021-L**: ±0.2%	±0.1%
DCR	± 0.1%	**11021**: ±0.1% **11021-L**: ±0.2%	±0.1%
θ	± 0.04°	**11021**: ±0.1% **11021-L**: ±0.2%	±0.1%
Measurement Speed	Fast: 15ms Med: 150ms Slow: 295ms (1kHz)	**11021** Fast: Freq=1k/10kHz 75ms Freq=100/120Hz 85ms Med: 145ms Slow: 325ms **11021-L** Fast: Freq=1kHz/10kHz 75ms Freq=40kHz 105ms Freq=50kHz 90ms Med: Freq=1kHz/10kHz 145ms Freq=40kHz 185ms Freq=50kHz 150ms Slow: Freq=1kHz/10kHz 325ms Freq=40kHz 415ms Freq=50kHz 400ms	Fast: 21ms
Communication Interface	RS-232C, Handler, USB storage, External bias current control, GPIB (option), LAN (option)	RS-232 (Standard), Handler & GPIB (Optional)	handler (50pin), GPIB, RS-232
Measurement Functions			
Trigger Mode	Internal, Manual, External, Bus	Internal, Manual, External, BUS	Internal, Manual, External, BUS
Range Switching Mode	Auto, Hold		
Equivalent Circuit Mode	Series, Parallel	Series, Parallel	Series, Parallel
Judgment	Compare, Bin-sorting	Bin-sorting, HI/GO/LOW	Bin-sorting & HI/GO/LOW

Feature	**11050 HF**	**11021/11021-L**	**11022/11025**
Bin Sorting		8 bin limits in %	8/99 bin limits in %, ABS
Comparator		Upper/Lower limits in value	Upper/Lower limits in value
Correction	Open/Short Zeroing, Load Correction	Open/Short zeroing	Open/ Short zeroing, load correction
Averaging			1~256 programmable
Test Sig. Level Monitor			Voltage, Current
Trigger Delay		0 ~ 9999mS	0~9999ms
Other			
Memory (Store/Recall)			50 instrument setups
Display	6.5 inch LCD display	40 x 4 (Character Module) LCD Display	240 x 64 dot-matrix LCD display
Operating Environment	Temperature : 10℃ ~ 40℃ Humidity : 10% ~ 75%	Temperature : 10˚C ~ 40˚C Humidity < 90 % R.H.	Temperature : 10˚C~40˚C Humidity : < 90 % R.H.
Power Consumption	80VA max.	50VA max.	65VA max
Power Requirement	90 ~ 132Vac or 180 ~ 264Vac, 47Hz ~ 63Hz	90 ~ 132Vac or 180 ~ 264Vac, 47 ~ 63Hz	90 ~ 132Vac or 180 ~ 264Vac, 47 ~ 63Hz
Dimensions (H x W x D)	Display Unit: 150 x 260 x 50 mm, 5.91 x 10.24 x 1.97 inch Measurement Unit: 65 x 390 x 320 mm, 2.56 x 15.35 x 12.60 inch	100 x 320 x 206.4 mm, 3.94 x 12.6 x 8.13 inch	100 x 320 x 347.25 mm, 3.94 x 12.6 x 13.67 inch
Weight	Approx. 7 kg / 15.43 lb.	4 kg / 8.81 lbs.	5.5 kg / 12.11 lbs.

LCR Accessory Selection Guide

Accessory				
Part #	**Description**	**11021 11021-L**	**11022 11025**	**11050**
A110104	SMD Test Cable #17	x	x	
A110211	Component Test Fixture	x	x	x
A110212	Component Remote Test Fixture	x	x	
A110232	4 BNC Test Cable with Clip#18	x	x	
A110234	High Frequency Test Cable	x	x	x
A110235	GPIB & Handler Interface	x		
A110236	19" Rack Mounting Kit	x	x	
A110239	4 Terminals SMD Electrical Capacitor Test Box (Patent)		x	
A110242	Battery ESR Test Kit	x	x	
A110244	High Capacitance Capacitor Test Fixture		x	
A110245	Ring Core Test Fixture		x	
A110501	4-Terminal SMD Test Fixture	x		
A113012	Vacuum Generator for A132574		x	
A113014	Vacuum Pump for A132574		x	
A132574	Test Fixture for SMD power choke		x	
A133004	SMD Test Box	x	x	
A133019	BNC Test Lead, 2M (single side open)		x	
A165009	4 BNC Test Cable with Probe	x	x	
A133509	GPIB Interface			x
A133510	LAN & USB-H Interface			x
A110104	SMD Test Cable #17	x	x	
A110211	Component Test Fixture	x	x	x
A110212	Component Remote Test Fixture	x	x	
A110232	4 BNC Test Cable with Clip#18	x	x	
A110234	High Frequency Test Cable	x	x	x

Chroma Systems Solutions Application Notes

Chroma has an extensive library of application notes.

See www.chromausa.com for the latest applications notes

Glossary

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

Capacitive Reactance (Xc)	Measurement of the actual AC resistance of a capacitor. How effective a capacitor is in allowing AC to flows depends upon its capacitance and frequency. $X_c = 1/2\pi fC$.
Clearance	The shortest distance between two conductors through air or insulating medium.
Compare	A procedure for sorting components by comparing the component’s measured value against a known standard.
Creepage	Creepage is the shortest path along the surface of an insulator or insulating medium that separates two conductors. The insulator or insulation medium cannot be air.
CSA	Canadian Standards Association.
Current Draw	The mains current consumed by the product or DUT.
DC	Direct current, non-reversing polarity. The movement of charge is in one direction. Used to describe both current and voltage. Batteries supply direct current.
Delay Time	The period during which an instrument waits to do a task.
Dielectric	An insulating material in which an electric field can be sustained with a minimum dissipation of power.
Dielectric Constant (K)	Ratio of the capacitance of a capacitor filled with a given dielectric to that same capacitor having only a vacuum as a dielectric.
Discharge	The act of draining off an electrical charge to ground. Devices that retain charge should be discharged after a DC hipot or IR test.
Dissipation Factor (D)	Synonym for loss tangent; a quantification of the loss in the capacitor Capacitance and dissipation factor for devices greater than 1000pF are tested at 1 KHz; devices of lower value are tested at 1 MHz. The testing of capacitors conforms to the guidance of military and industry standards
DUT	Device Under Test - the product being tested.
Dwell Time	The amount of time the DUT is allowed to stabilize at the test voltage before measurements are performed.
Electric Current (I)	The flow of electrons (or electron "holes") through a conducting material, which may be a solid, liquid, or gas; the rate of flow of charge past a given point in an electric circuit. The magnitude of current flow through the

	conductor is proportional to the magnitude of voltage or electrical potential applied across the conductor and inversely proportional to the resistance (or impedance) of the conductor. Current is expressed in amperes or milliamperes (amperes/1000).
Equivalent Circuit	The configuration of the device under test. The components of the DUT can be represented as a series or parallel equivalent circuit.
Fall Time	The amount of time it takes to gradually decrease the voltage to zero potential.
Frequency (f)	The rate at which a current or voltage reverses polarity and then back again completing a full cycle, measured in Hertz (Hz) or cycles per second.
GFCI	Ground Fault Circuit Interrupter, a safety device that breaks a power circuit as soon as it detects current flow of a certain magnitude through the ground return of a power circuit. Also known as GFI.
Ground	The base reference from which voltages are measured, nominally the same potential as the earth. Also the side of a circuit that is at the same potential as the base reference.
Handler	Device for remote control of test instrument in component handling operations.
Hertz (Hz)	The unit of measure of frequency, equivalent to cycles per second.
High Limit	The upper value for a test to be considered a PASS. If the measured value is higher than the high limit the test is considered a FAIL. In hipot, leakage current and ground bond tests a high limit is required.
IEEE	Institute of Electrical and Electronic Engineers.
IEEE 488	General Purpose Interface Bus (GPIB) - an industry standard definition of a parallel bus connection for the purpose of communicating data between devices.
Impedance (Z)	A vector summation of resistance (R) and reactance (X). A term used with alternating current circuits to describe the "AC resistance" to the flow of current through a circuit when an AC voltage is applied across the terminals of that circuit. Impedance is a complex quantity composed of real (in phase with voltage) and reactive (out of phase by 90°) components. Impedance is calculated as voltage divided by current. Capacitors: Reactance = $X_C = 1/j\omega C$ Inductors: Reactance = $X_L = j\omega L$ Resistors: Resistance = R

	Z = $\sqrt{X^2 + R^2}$
Inductor	L (as in LCR). An inductor is a coil of wire. It is used to create electromagnetic induction in a circuit.
Inductance (L)	The property of a coil to oppose any change in current through it. If the turns (coils) of the wire are stretched out, the intensity of the magnetic field will diminish and the inductance will be less. Unit of measure is the Henry (H).
Inductive Reactance	A measure of how much the electro-magnetic force (emf) of a coil will oppose current variation through the coil. The amount of reactance is directly proportional to the current variation: $X_L = 2\pi fL$.
Insulation	The protection against unwanted flow of current through a path, as between a circuit of a product and the ground reference. Materials that prevent current flow are referred to as insulators or dielectrics.
Kelvin Connection	A circuit connection that automatically compensates for measurement errors caused by resistance of leads between a tester and the point of measurement on a DUT.
Level	The test signal level is the programmed RMS voltage of the generator in an LCR meter. The actual test voltage across the DUT is always less than the programmed level.
Load	The total resistance or impedance of all circuits and devices connected to a voltage source.
Low Limit	The lower value for a test to be considered a PASS. If the measured value is lower than the low limit the test is considered a FAIL.
Megohmmeter	An instrument designed to measure high values of resistance using a DC voltage usually greater than 50 V DC.
Milliohmmeter	An instrument designed to measure low values of resistance using a DC current or voltage.
NIST	National Institute of Standards and Technology, an agency of the U.S. Government that sets standards for physical measurements and references, formerly called the National Bureau of Standards.
NRTL	Nationally Recognized Testing Laboratory, such as Underwriters Laboratories (UL), Factory Mutual (FM), or Canadian Standards Association (CSA).

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

Prefixes	The prefixes for Multiple Scientific Engineering Symbols are:

1000000000000000	1015	Peta	P
1000000000000	1012	Tera	T
1000000000	109	Giga	G
1000000	106	Mega	M
1000	103	Kilo	k
0.001	10-3	milli	m
0.000001	10-6	micro	m
0.000000001	10-9	nano	n
0.000000000001	10-12	pico	p
0.000000000000001	10-15	femto	f

Protective Earth	Conductor that connects between any protectively earthed parts of a Class I product and an external protective earth connection.
Microsecond	One millionth of a second.
Q (Quality Factor)	The ratio between the energy stored in a circuit (in C and L) and the energy dissipated (by R):
Range	The resistance ranges the test instrument uses for reference in making the measurement.
Reactive	The component of an AC voltage, current, or impedance that is 90° out of phase with the "real" or in phase component. Reactive components are associated with capacitive or inductive circuits.
Real	The component of a voltage, current, or impedance that is in phase with the "real" component. Real components are associated with purely resistive circuits.
Regulation	When applied to electrical circuits, regulation refers to the variation in output voltage that occurs when the input voltage changes or when the connected load changes. When applied to test laboratories and agencies, refers to the control exercised by these entities over test specs and rules.
Repeatability	The difference between successive measurements with no changes in the test setup or test conditions.
Reproducibility	Similar to repeatability but adds the element of what could be expected under real life conditions. Reproducibility would take into account the variability in things like fixtures, where the DUT being tested is removed from the fixture and re-inserted.

Resolution	The smallest value that can be shown on the display in a digital instrument. LCR meters typically specify a measurement range that is the largest and smallest value that can be shown on that meter’s display.
Resistance (R)	The electrical characteristic that impedes the flow of current through a circuit to which voltage has been applied. Resistance is calculated by Ohm's Law as voltage divided by current (for DC circuits). For AC circuits, it is the in-phase or "real" component of impedance. Units are expressed in ohms (Ω).
RS232	An industry standard definition for a serial line communication link or port.
Scanner	A scanner is a device designed to switch or matrix signals.
SCC	Standards Council of Canada, an agency of the Canadian Government analogous to OSHA in the United States.
Speed	The rate per second at which the instrument makes a measurement. Speed is inversely proportional to accuracy.
Spike	A large momentary deviation from a normal voltage or current waveform.
Stabilization Time	The time required for a transient disturbance to decay to a steady state value.
Source Impedance	The impedance of the measuring instrument applied to the input terminals of the device under test (DUT). If 1V is the programmed voltage and the source impedance is 25 Ω and the DUT is 25 Ω, then the voltage at the DUT is 0.5V.
Trigger	The device for initiating the test (applying the voltage or current).
External Trigger	The test is initiated via an external source such as a computer with an IEEE-488 or Handler interface. One measurement is made each time the external trigger is asserted.
Internal Trigger	The instrument continuously makes measurements.
Manual Trigger	The operator initiates the test by pressing the [START] button. One measurement is made each time the trigger is pressed.
UL	Underwriters Laboratories, Inc., an NRTL located in Illinois.
Voltage (V)	The electrical potential applied to a circuit.
Waveform	The instantaneous value of a variable such as voltage or current plotted against time.

X (Reactance)	Reactance is the imaginary component of Impedance.
Y (Admittance)	Admittance is the reciprocal of Impedance. Y = 1/Z
Z (Impedance)	Impedance is the sum of alternating current oppositions (capacitive reactance, inductive reactance, and resistance). Z = R