QuadTech

Application Note

A Guide to LCR Measurements

Impedance is the basic passive electrical quantity of all materials or components. It is defined as the ratio of the voltage applied to the device and the resulting current through it. The basic elements that make up electrical impedances are resistance, inductance and capacitance, R, L and C. The new generation of LCR meters is capable of displaying these parameters and can also easily calculate and display many other parameters such as Z, Y, X, G, B, D, etc. What are these terms and of what importance are they? This note is intended as an aid in understanding which AC measurements are typically used and as a guide to performing accurate and meaningful impedance measurements with 7000 Series Impedance Meters.

Figure 1: QuadTech 7600 Precision RLC Meter

Impedance (Z)

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

Note:

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

Vector Diagrams and Number Prefixes

The phase shift can be drawn in a vector diagram that shows the impedance Z, its real part R_S, its imaginary part jX_S (reactance), and the phase angle θ. Because series impedances add, an equivalent circuit for an impedance would put R_S and X_S is *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 Φ. Note $\Phi = -\theta$. 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, $G_P \neq 1/R_S$ and $B_P \neq -1/X_S$.

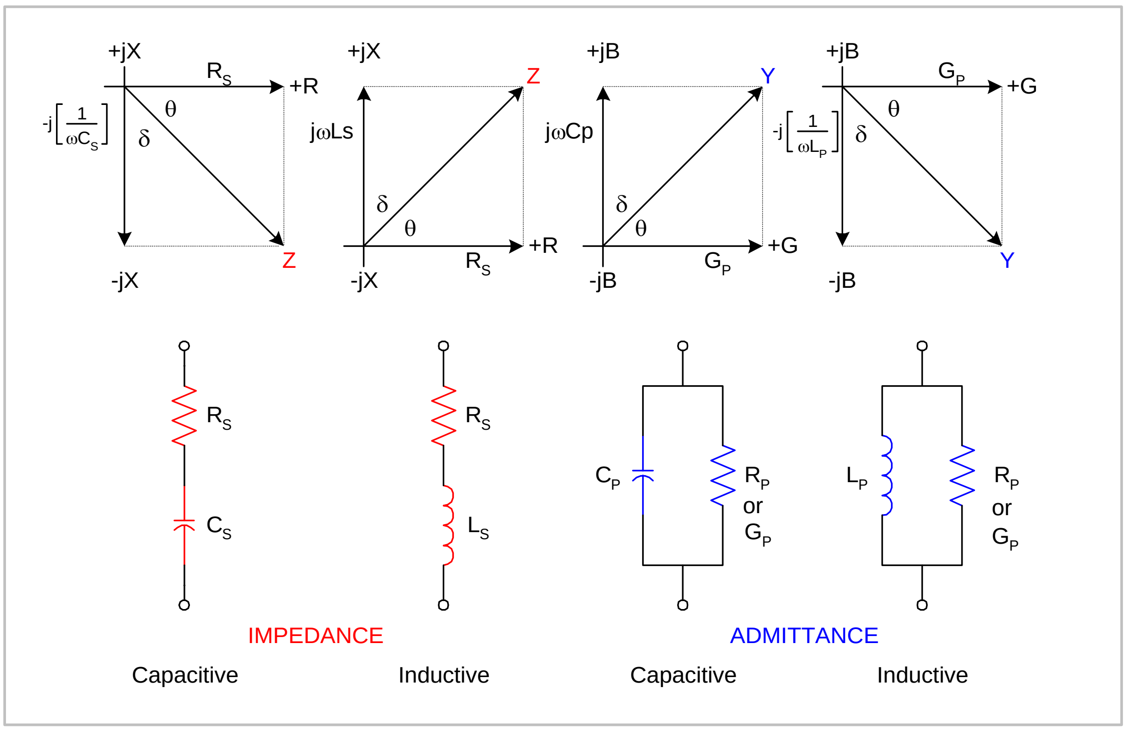
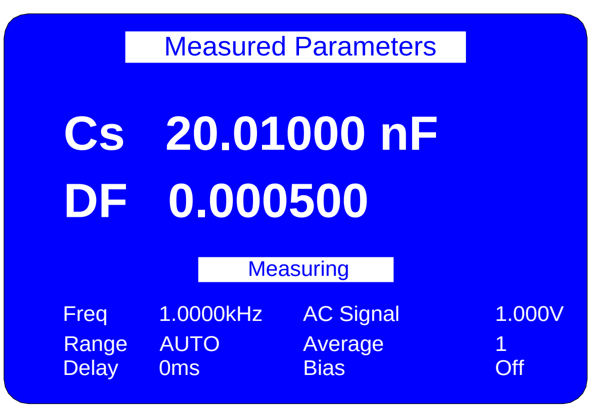


Figure 2: Phase Diagrams

Display of Measured Impedance Value



The 7000 Series LCR Meters have the ability to display units in Engineering terms or Scientific notation, whichever the user would prefer. As an example, a 7000 Series instrument will display a 0.00000002001farad capacitor as 20.01000 nF or $2.00100e^{-08}$F

Table 1 lists the number prefixes with both scientific and engineering notation terms.

Table 1: Number Prefixes

Multiple	Scientific	Engineering	Symbol
1000000000000000	10^{15}	Peta	P
1000000000000	10^{12}	Tera	T
1000000000	10^{9}	Giga	G
1000000	10^{6}	Mega	M
1000	10^{3}	Kilo	k
.001	10^{-3}	milli	m
.000001	10^{-6}	micro	µ
.000000001	10^{-9}	nano	n
.000000000001	10^{-12}	pico	p
.000000000000001	10^{-15}	femto	f

The 7000 Series instrument allows for 2, 3 or 4 terminal connections to the unknown impedance. The proper connection method is determined by the value of the measured impedance and the test accuracy required. Two-terminal is the most common and simplest connection method and is typically used in the impedance range of 100 Ω to 10kΩ. Three-terminal (2-terminal + guard) measurements are useful for high impedances when the affects of stray capacitance can introduce errors and also when guarded in-circuit measurements are necessary. Four-terminal (Kelvin, 2 current + 2 potential) measurements are required for accurate low impedance measurements (less than 100Ω). This method eliminates series impedances and contact resistance errors. Five-Terminal (3 terminal + 4 terminal) is less commonly used and produces accurate measurements over a wide impedance range.

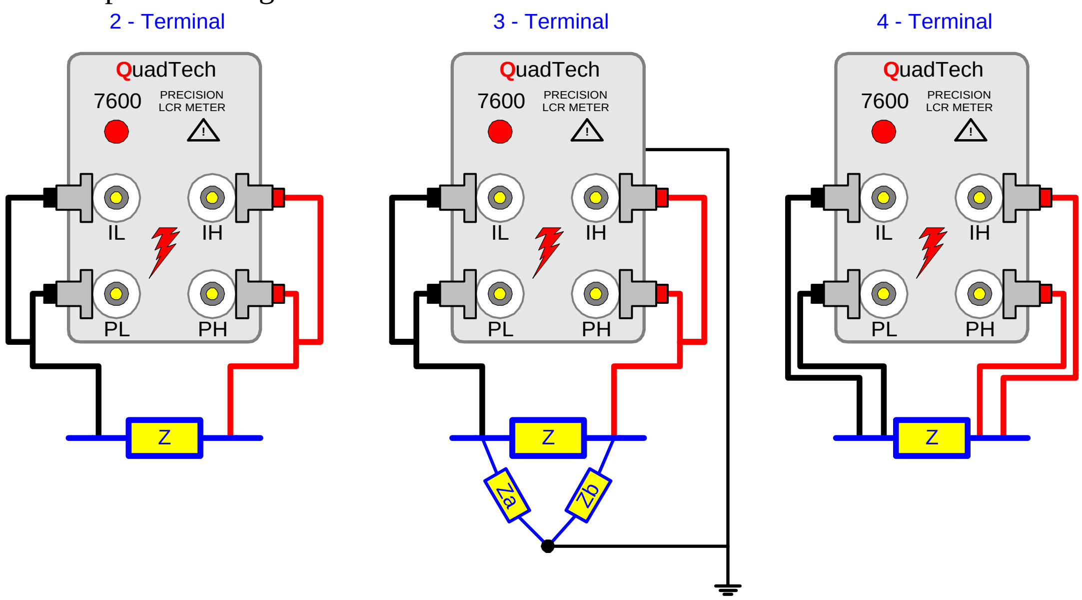


Figure 3: Connection to DUT

Impedance Parameters – Table 2

The 7000 Series instruments allow for the display of any two parameters from a choice of 15. An impedance measurement will produce the magnitude of G and B and mathematical relationships will produce the magnitude of any other parameter desired. Table 2 lists the displayed parameters and gives units and the basic mathematical formulae for each.

Parameter	Quantity	Unit Symbol	Formula
Z	Impedance	ohm, Ω	$Z = R_S + jX_S = \frac{1}{Y} = \|Z\| \varepsilon^{j\theta}$
|Z|	Magnitude of Z	ohm, Ω	$\|Z\| = \sqrt{R_S{}^2 + X_S{}^2} = \frac{1}{\|Y\|}$
R_S or ESR	Resistance, Real part of Z	ohm, Ω	$R_S = \frac{G_P}{G_P{}^2 + B_P{}^2} = \frac{R_P}{1+Q^2}$
X_S	Reactance, Imaginary part of Z	ohm, Ω	$X_S = -\frac{B_P}{G_P{}^2 + B_P{}^2}$
Y	Admittance	siemen, S	$Y = G_P + jB_P = \frac{1}{Z} = \|Y\| \varepsilon^{j\phi}$
|Y|	Magnitude of Y	siemen, S (was mho)	$\|Y\| = \sqrt{G_P{}^2 + B_P{}^2} = \frac{1}{\|Z\|}$
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, DF or tan δ	Dissipation factor	none	$D = -\frac{1}{Q} = \frac{R_S}{X_S} = \frac{G_P}{B_P} = \tan(90^0 - \theta) = \tan\delta$
θ	Phase angle of Z	degree or radian	$\theta = -\phi$
ϕ	Phase angle of Y	degree or radian	$\phi = -\theta$

Notes: f = frequency in Hertz, $j = \sqrt{-1}$, $\omega = 2\pi f$

R and X are equivalent **series** quantities unless otherwise defined. G and B are equivalent **parallel** quantities unless otherwise defined.
We sometimes use parallel R (R_p) but rarely use parallel X, and very rarely series G or series B.

C and L each have two values, series and parallel. If not defined usually we mean the series values, but not necessarily, especially for C (Cp is common, Lp is less used).
We define Q as being positive if it is inductive, negative if it is capacitive, We define D as positive if capacitive. Thus D = -1/Q.
Some people (particularly in Europe) use tan δ instead of D, tan δ = D.

Typical Impedance Measurements

Manufacturers and end-users commonly measure passive components such as resistors, capacitors and inductors to determine the proper value and response to changes in testing parameters. The basic measurement parameters, such as voltage, frequency, equivalent circuit, etc. are usually determined by national, international and manufacturer specifications. The following may be used as a guideline, but refer to specific industry standards when in doubt.

Materials are measured to determine their electrical characteristics. This includes insulating materials such as plastics, conductive materials, anything, and even rocks. Measurements on these devices are used to quantitize properties for many varied applications. Often these materials are measured in a dielectric cell designed to hold the material and to produce repeatable measurement results.

Transformers and Motors are unique forms of an inductor and require several types of impedance measurements. They require inductance measurements of windings, capacitance between windings, resistance and other unique tests.

Cables are measured to determine capacitance between wires or to shield characteristic impedance, inductance, and resistance. The type of cable and its end use determines the measurement parameters of the cable.

Battery impedance is measured to provide an indication of the ability of the battery to hold a charge and to deliver specified current.

Other typical impedance measurements would create a list quite long. Circuit board track capacitance, network response, transducer impedance, filter networks, etc. The ability of the impedance tester to provide a wide variety of measurement conditions is key to successful impedance measurements.

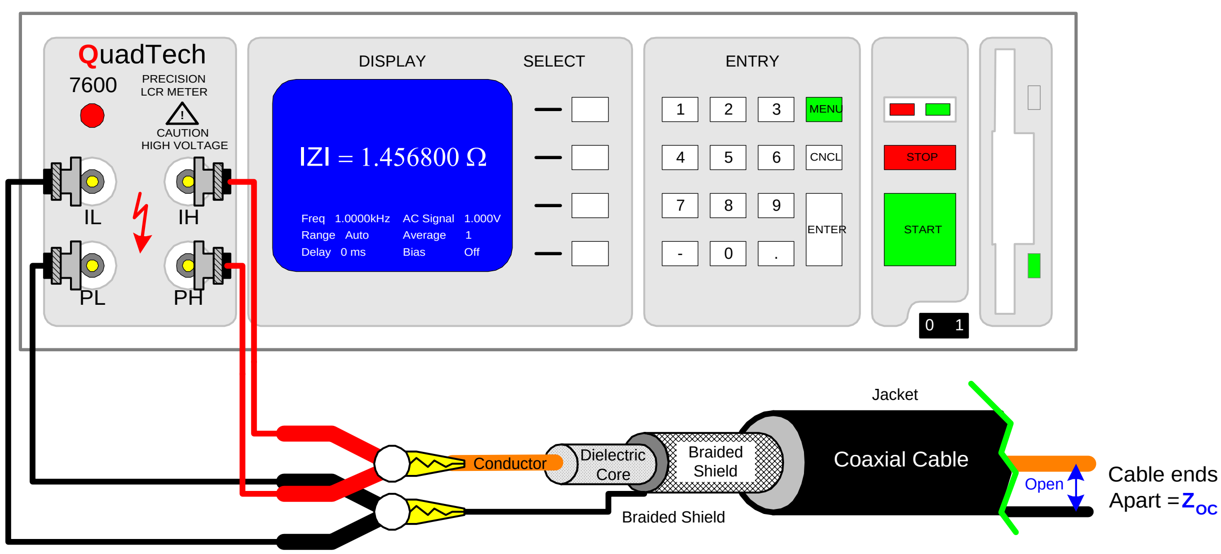


Figure 4: Characteristic Cable Impedance (Zo) Measurement using 7600 LCR Meter

Typical Impedance Measurement Parameters

Table 3: 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
"	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, 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

Measurement Conditions

As previously stated, measurement test conditions are determined by component specifications, national and international standards, and by the application of the device itself. Typical test frequencies are 60Hz, 120Hz, 1kHz, and 1MHz. Commonly, lower impedances are tested with lower frequencies and vice versa. Inductors are often specified at the frequency at which they will be used. Test voltages are usually .1V or 1V. Special cases such as semiconductor capacitance measurements may require voltages in the low milli-volt range and noisy measurements such as cable capacitance require high voltages to improve the signal to noise ratio. Test current specifications are often applied to small inductors where changes in current affect the inductance of the device.

Specific impedance testing requirements for a particular type of measurement can become very complicated and confusing. Questions such as “What’s series and parallel?”, “What does two, three and four terminal mean?”, “What is ESR of a capacitor?”, “What is a dielectric cell?” are all frequently asked. For detailed information on these subjects and others call our toll free number for an application note or assistance.

Conclusion

Precision digital LCR meters offer a wide variety of test parameters and conditions to meet most impedance measurement requirements. Not only do they offer all the basic requirements, they also contain features that make the measurements faster, more repeatable, and very accurate. The 7000 Series offers virtually every frequency below 2MHz, a wide voltage and current range, and test leads and fixtures for most common measurements. Other features are provided that can enhance the basic impedance measurement. Averaging a number of readings to improve accuracy, communication ports for computer interfaces, internal data storage on floppy disk for further data analysis, internal storage of setup conditions for error free setups, fixture stray impedance zeroing and others. Some of these features can improve measurement accuracies and others aid in data manipulation.

For complete product specifications on the 7000 Series Precision LCR meters or any of QuadTech’s products, visit us at http://www.quadtech.com/products. Call us at 1-800-253-1230 or email your questions to info@quadtech.com.

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