QuadTech

Application Note

What is the Accuracy Anyway?

Let's take a closer look at how accuracy is specified in an impedance-measuring instrument and how to calculate the accuracy of several different LCR meters. An LCR meter is an instrument that measures the primary impedance parameters of inductance (L), capacitance (C) and resistance (R). It can also measure secondary parameters DF, Q, phase and ESR.

Definitions of accuracy, resolution, repeatability, reproducibility and impedance are provided for clarity. Discussions of how an LCR meter works and the difference between basic and actual accuracy is presented also. Measurement parameters such as DUT impedance, frequency, resolution and speed and their affects on accuracy are considered. Examples of instrument accuracy for QuadTech's 1689 Digibridge, 7600 Precision LCR Meter and 1910 Inductance Analyzer are given for your analysis.

Definitions

Accuracy is defined as 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 secondary value. For example: ±0.05% for L, C & R and ±0.0005 for Df.

Resolution is another parameter that needs to be considered. Resolution is 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 the display.

Repeatability is the difference between successive measurements with no changes in the test setup or test conditions.

Reproducibility is similar to repeatability but adds the element of what could be expected under real life conditions. Reproducibility would take into account the variability in thing like fixturing where the DUT being tested is removed from the fixture and then inserted again.

Impedance is the AC resistance of the DUT. Impedance Z is a vector summation of resistance R and reactance X.
For capacitors reactance is defined as $X_C = 1/j\omega C$
For inductors reactance is defined as $X_L = j\omega L$
For resistors resistance is defined as R
Impedance is defined as $Z = \sqrt{(X^2 + R^2)}$

How an LCR meter works

There are four terminals on an LCR meter. PH and PL are the two terminals that measure the voltage across the DUT. IH and IL are the two terminals that provide the signal and measure the current flowing through the DUT. It also needs to be noted that in order to measure the current a resistor is placed in series with the signal source. This is referred to as the source resistance. These connections are shown in Figure 1.0.

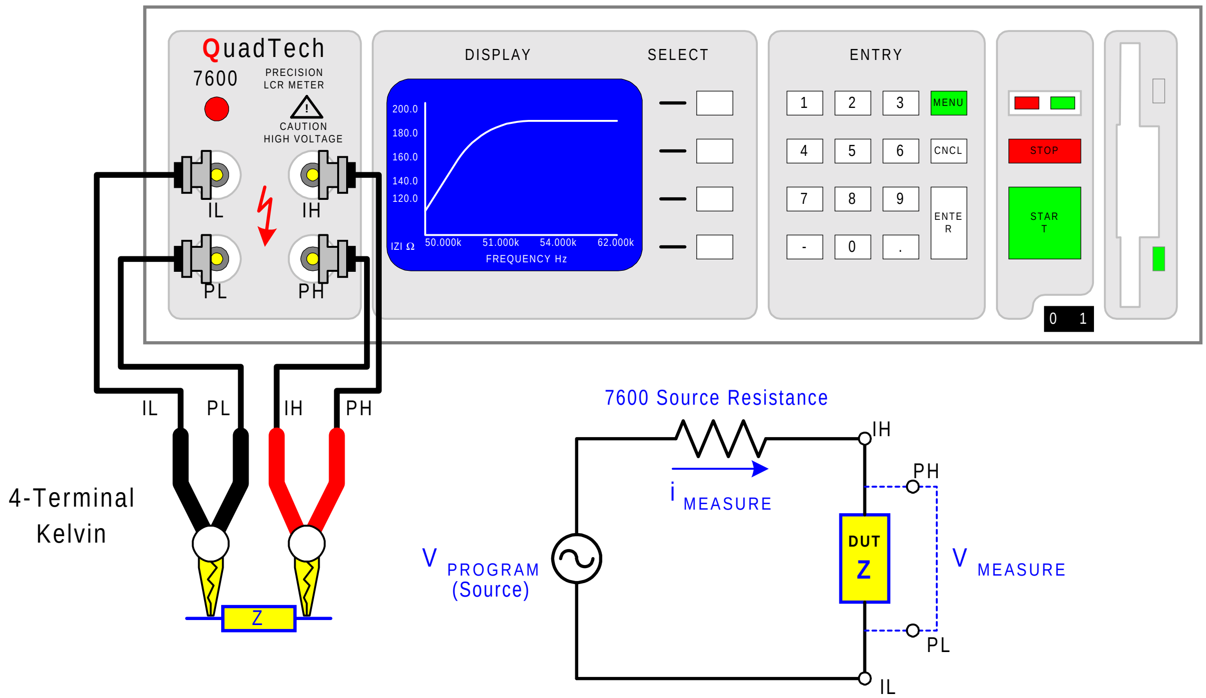


Figure 1.0: Four-Terminal Connection and Source Resistance

An LCR meter measures the current flowing through the DUT and voltage across the DUT using the four-terminal connection. The phase shift between the voltage and current signals is also determined. Knowing the voltage and current allows the LCR meter to use Ohm's Law ($Z = V/I$) to calculate the magnitude of the impedance. The impedance combined with the phase angle allows the determination of impedance and resistance using the formulas $X = Z * \text{Sin}(\phi)$ and $R = Z * \text{Cos}(\phi)$. Using these values all other parameters can be calculated such as L and C.

Accuracy: Basic or Actual?

Basic Accuracy

Manufacturers of LCR meters specify basic accuracy. This is the best-case accuracy that can be expected. Basic accuracy does not take into account error due to fixturing or cables. There are also techniques that can be used to improve measurement accuracy. These techniques will be discussed in another article on averaging, median mode and load correction.

The basic accuracy is specified at optimum test signal, frequencies, highest accuracy setting or slowest measurement speed and impedance of the DUT. As a general rule this means 1VAC RMS signal level, 1kHz frequency, high accuracy which equates to 1 measurement/second, and a DUT impedance between 10Ω and 100kΩ.

Typical LCR meters have a basic accuracy between ±0.01% and ±0.5%.

Actual Accuracy

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

It is also important to understand that the measurement range is really more a display range. For example an LCR will specify a measurement range of 0.001nH to 99.999H this does not mean you can accurately measure a 0.001nH inductor or a 99.9999H inductor, but you can perform a measurement and the display resolution will go down to 0.001nH or up to 99.999H. This is really why it is important to check the accuracy of the measurement you want to perform. Do not assume that just because the value you want to measure is within the measurement range you can accurately measure it.

The accuracy formulas take into account each of the conditions effecting accuracy. Most common are measurement range, accuracy/speed, test frequency and voltage level. There are addition errors including dissipation factor Df of the DUT, internal source impedance and ranges of the instrument, that effect accuracy.

Factors Affecting Accuracy Calculations

DUT Impedance

High impedance measurements increase the error because it is difficult to measure the current flowing through the DUT. For example if the impedance is greater than 1MΩ and the test voltage is one volt there will be less than 1µA of current flowing through the DUT. The inability to accurately measure the current causes an increase in error.

Low impedance measurements have an increase in error because it is difficult to measure the voltage across the DUT. Most LCR Meters have a resistance in series with the source of 100, 50, 25, 10 or 5 ohms. As the impedance of the DUT approaches the internal source resistance the voltage across the DUT drops proportionally. If the impedance of the DUT is significantly less than the internal source resistance then the voltage across the DUT becomes extremely small and difficult to measure causing an increase in error.

More Factors Affecting Accuracy Calculations

Frequency

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

Resolution

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

Accuracy and Speed

Accuracy and speed are inversely proportional. That is the more accurate a measurement the more time it takes. LCR meters will generally have 3 measurement speeds. The measurement speed can also be referred to as measurement time or integration time. Basic accuracy is always specified with the slowest measurement speed, generally 1 second for measurements above 1kHz. At lower frequencies measurement times can take even longer because the measurement speed refers to the integration or averaging of at least one complete cycle of the stimulus voltage. For example, if measurements are to be made at 10Hz, the time to complete one cycle is 1/frequency = 1/10Hz = 100 milliseconds. Therefore the minimum measurement speed would be 100ms.

Dissipation Factor (Df) or Quality Factor (Q)

Df and Q are reciprocals of one another. Df = 1/q and Q = 1/Df. The importance of Df or Q is the fact that they represent the ratio of resistance to reactance or vice versa. This means that the ratio Q represents the tangent of the phase angle. As phase is another measurement that an LCR meter must make, this error needs to be considered. When the resistance or reactance is much much greater than the other, the phase angle will approach ±90° or 0°. As shown in Figure 2.0, even small changes in phase at -90° result in large changes in the value of resistance, R.

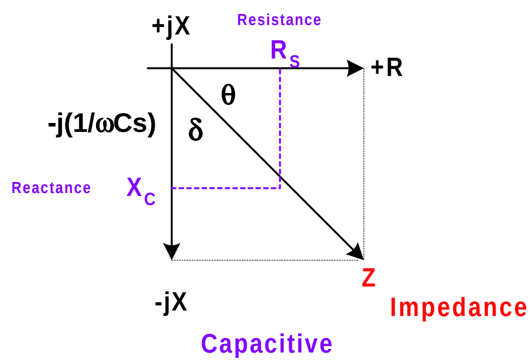


Figure 2.0: Phase Diagram for Capacitance

Overall this concludes that the LCR meter may be able to accurately measure the primary parameter such as inductance (L) or capacitance (C) but be unable to accurately measure the secondary parameter such as resistance (R) or dissipation factor (Df).

Accuracy Formulas and Graphs of QuadTech LCR Meters

1689 Digibridge

The accuracy shown above can be broken down into the various components effecting accuracy. This can be seen in the 1689 Accuracy Formula for Resistance:

$$R = 0.01\% \left[\left(1 + Kcv\right) \text{ or } \left(\frac{Rx}{Rmax}\right) \text{ or } \left(\frac{Rmin}{Rx}\right) \right] \left(1 + |Q|\right)\left(1 + Ks + Kfv\right) + 0.01\%$$

Where:

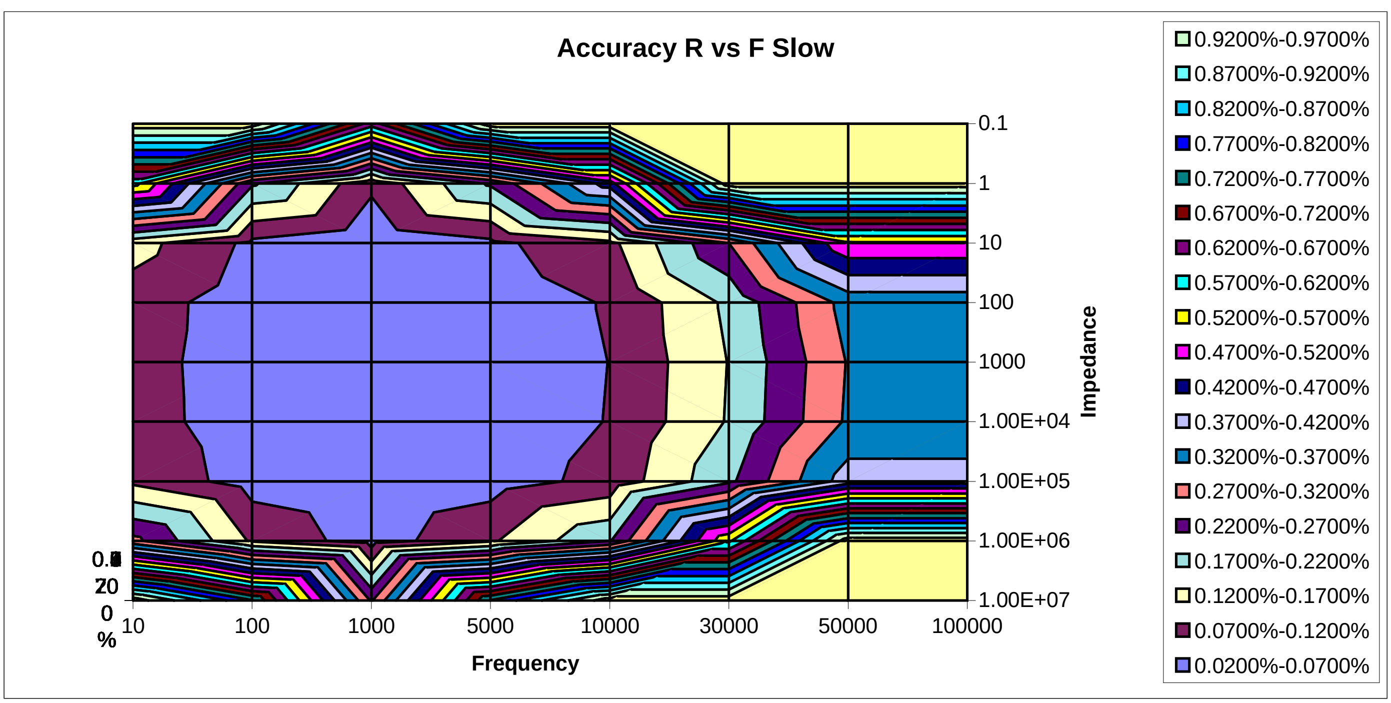
$(1 + K_{cv})$ takes into account Constant vs. Non-Constant Voltage source
R_x/R_{max} takes into account maximum measurement range
R_{min}/R_x takes into account minimum measurement range
$(1 + Q)$ take into account ratio of resistance to reactance
$(1 + K_s + K_{fv})$ takes into account K_s (measurement speed/Accuracy) and K_{fv} (frequency and voltage level)

For the 1689 instrument, various constants are given for Kcv, Ks and Kfv depending upon how the LCR meter is programmed for signal voltage and frequency. These constants vary from 0 to 100 with 0 being the optimum measurement case.

An LCR meter can either give the formula so one can calculate the actual accuracy and/or present the accuracy tables as a graph.

Graph

The type of graph used for accuracy of an LCR meter is referred to as a bathtub curve. It looks very similar to a topographical map. Below is a graph of accuracy for the 1689 LCR Meter vs. Frequency and Resistance. As you can see the basic accuracy of 0.02%, shown in blue, covers a frequency range from 5Hz to 10kHz and an impedance range from 10Ω to 1MΩ



Example: 1689 Accuracy Calculation

1689 Digibridge: Accuracy Calculation

Conditions: 1nF Capacitor at 100kHz, 1VAC signal, Auto Range, Non-Constant Voltage, Slow Measurement Speed and a Df of 0.001.

Basic Accuracy of the 1689 is specified at ±0.02%

Actual Accuracy of the 1689 is ±0.32% based upon formula below:
Cmax = 25uF/f =25 x 10^{-6}/100 = 250 x 10^{-9}
Cmin = 6.4nF/f = 6.4 x 10^{-9}/100 = 64 x 10^{-12}
f = frequency in kHz = 100 (For frequencies >20kHz, Cmin = 6.4nF/f)
Kcv = 0
Ks = 0
Kfv = 30
D = Df = 0.001

$$C = 0.01\% \left[\left(1 + K_{cv}\right) \text{ or } \left(\frac{C_x}{C_{max}}\right) \text{ or } \left(\frac{C_{min}}{C_x}\right) \right] \left(1 + |D|\right) \left(1 + K_s + K_{fv}\right) + 0.01\%$$

$$C = 0.01\% \left[\left(1 + 0\right) \text{ or } \left(\frac{1 \times 10^{-9}}{250 \times 10^{-9}}\right) \text{ or } \left(\frac{64 \times 10^{-12}}{1 \times 10^{-9}}\right) \right] \left(1 + |0.001|\right) \left(1 + 0 + 30\right) + 0.01\%$$

$$C = 0.01\% \left[\left(1\right) \text{ or } \left(.004\right) \text{ or } \left(.064\right) \right] \left(1.001\right) \left(31\right) + 0.01\%$$

$$C = 0.01\% \left[31.031 \right] + 0.01\%$$

$$C = 0.32\%$$

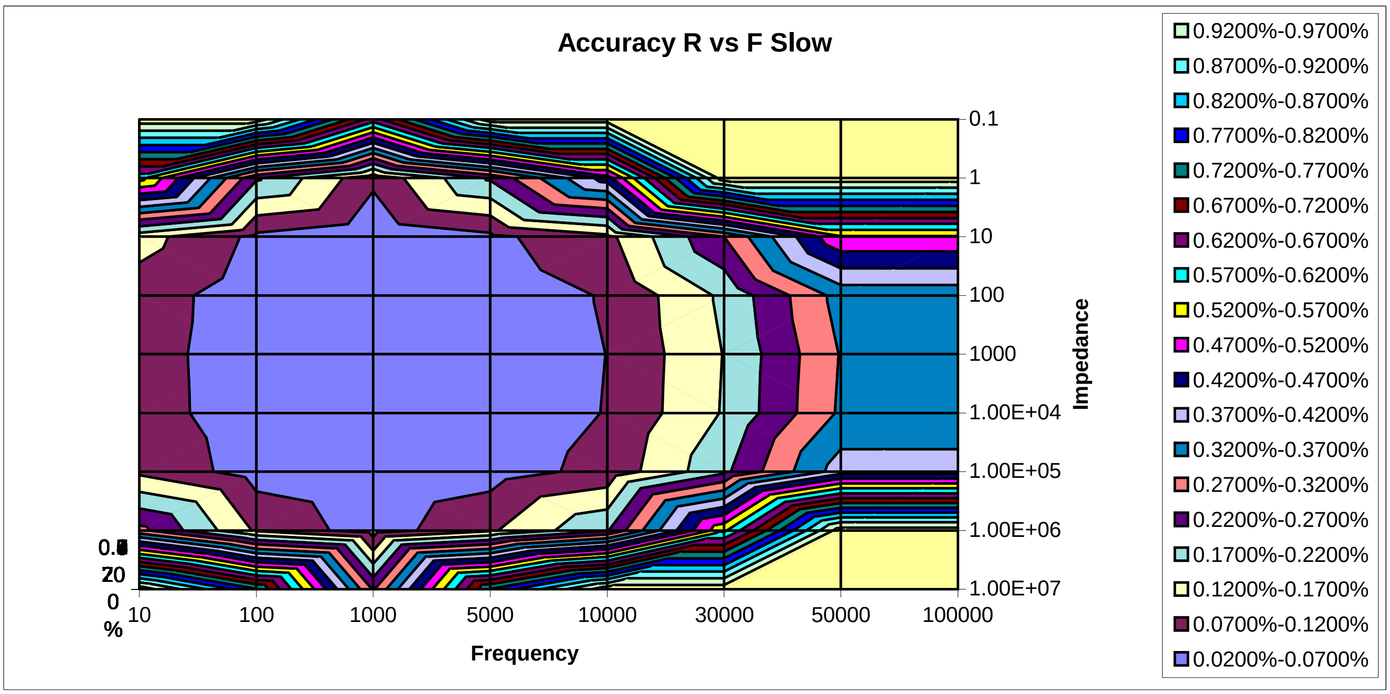
Example: 1689 Accuracy Graph

The accuracy could have been predicted without the use of a formula. If we calculate the impedance of a 1nF capacitor at 100kHz we get a value of:

$Z \approx Xs = 1/(2\pi*\text{frequency}*\text{capacitance})$

$Z \approx Xs = 1/(2\pi*100000*0.000,000,001) = 1591\text{ohms}$

Use the graph below and substitute Z for R. If we find the position on the graph for an impedance value of 1591ohms at 100kHz we see a darker blue are representing an accuracy of 0.32% to 0.37%. Overall the graph and formula point to the same accuracy of ±0.32%.



Example: 7600 Accuracy Calculation

7600 Precision LCR Meter: Accuracy Formula

Conditions: 1pF Capacitor at 1MHz, 1VAC signal, Auto Range, Non-Constant Voltage, Slow Measurement Speed and a Df of 0.001.

Basic Accuracy of the 7600 is ±0.05%

Accuracy Formula is:

For Slow Mode, R, L, C, X, G, B, |Z|, and |Y|

$$A\% = +/- \left[0.025 + \left(\left(0.025 + \frac{.05}{|Z_m|} + \left(|Z_m| \times 10^{-7}\right)\right) \times \left(\frac{.02}{V_S} + .08 \times \frac{V_{fs}}{V_S} + \frac{(V_S - 1)^2}{4}\right) \times \left(0.7 + \frac{F_m}{10^5} + \frac{300}{F_m}\right)\right)\right] \times K_t$$

V_S = Test voltage in voltage mode, I * Z_m in current mode*

Z_m = Impedance of DUT

F_m = Test frequency

K_t = 1 for 18° to 28°C

2 for 8° to 38°C

4 for 5° to 45°C

* For I * Z_m > 3, accuracy is not specified

V_{FS} = 5.0 for 1.000V < V_S ≤ 5.000V

1.0 for 0.100V < V_S ≤ 1.000V

0.1 for 0.020V ≤ V_S ≤ 0.100V

For Zm > 4* ZRANGE multiply A% by 2
For Zm > 16* ZRANGE multiply A% by 4
For Zm > 64* ZRANGE multiply A% by 8

	In Voltage Mode	In Current Mode
ZRANGE =	100kΩ for Zm ≥ 25kΩ	400Ω for I < 2.5mA
	6kΩ for 1.6kΩ ≤ Zm < 25kΩ	25Ω for I > 2.5mA
	6kΩ for Zm > 25kΩ and Fm > 25kHz	
	400Ω for 100Ω ≤ Zm < 1.6kΩ	
	400Ω for Zm > 1.6kΩ and Fm > 250kHz	
	25Ω for Zm < 100Ω	

Example: 7600 Accuracy Calculation & Graph

Calculated Accuracy using the formula is ±3.7%.
Kt = 1
Zm = 1/(2*π*frequency*C) = 1/(2*π*1000000*1x10^{-12}) = 159kohms
Zrange = 400 ohms
Vfs = 1
Multiply A% = 8

$$A\% = +/- \left[0.025 + \left(\left(0.025 + \frac{.05}{|159000|}\right) + \left(|159000| \times 10^{-7}\right)\right) \times \left(\frac{.02}{1} + .08 \times \frac{1}{1} + \frac{(1-1)^2}{4}\right) \times \left(0.7 + \frac{1000000}{10^5} + \frac{300}{1000000}\right)\right] \times 1$$

A% = 0.46%

Multiply A% times 8 due to Zm > 64 times Zrange

A% **=** 0.46% * 8 **= 3.68%**

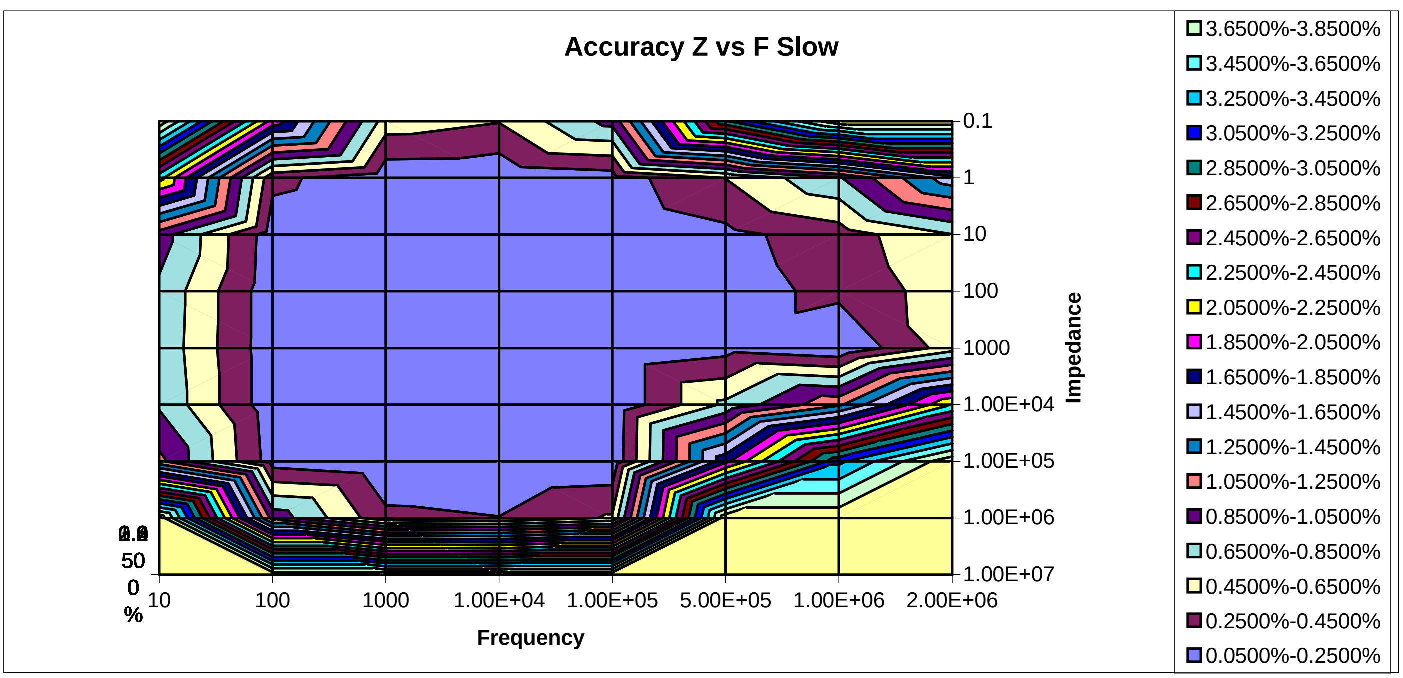
7600 Graph

The accuracy could have been predicted without the use of a formula. If we calculate the impedance of a 1pF capacitor at 159kHz we get a value of:

Z ≈ Xs = 1/(2π*frequency*capacitance)

Z ≈ Xs = 1/(2π*1,000,000*0.000,000,000,001) = 159kohms

Use the graph below and substitute Z for R. If we find the position on the graph for an impedance value of 1591ohms at 100kHz we see a light blue or teal representing an accuracy of 3.45% to 3.65%. Overall the graph and formula point to the same accuracy of ±3.5%.



Example: 1900 Accuracy Calculation

1910 Inductance Analyzer: Accuracy Calculation

Conditions: 33nH Inductor at 1MHz, 1VAC signal, Auto Range, Non-Constant Voltage, and Slow Measurement Speed.

Basic Accuracy of the 1910 is ±0.1%

Accuracy Formula for the 1910 is:

<u>Basic Accuracy For AC:</u>

High 0.10%
Medium 0.25%
Low & Low No Display 0.5%

The actual accuracy at a given test condition is defined by the following formula:

$$\text{Accuracy} = \quad Acc_{Basic} \sqrt[\frac{3}{2}]{\frac{1}{V}} \left[\left(1 + \frac{50}{Freq} + \frac{Freq}{200k} \right) \left(1 + \frac{|Z|}{Z_{MAX}} + \frac{1}{|Z|} \right) \right]$$

V = Programmed test voltage (V_{SOURCE})
Freq = Programmed test frequency
|Z| = DUT impedance

Note: For frequencies above 100kHz V_{DUT} must be at least 20mV. That is $V_{DUT}=V_{SOURCE}*(Z_{DUT}/Z_{DUT}+R_{SOURCE})$

Z_{Max} is $4*10^5$ for Frequency less than 10kHz
$2.5*10^4$ for Frequency less than 250kHz
$1.5*10^3$ for Frequency above 250kHz

1910 Calculated Accuracy

Calculated Accuracy using the formula is ±3.5%.

V = 1Volt
AccBasic = 0.1%
Freq = 1MHz
Z_{Max} = 1500 ohms
$Z = 2*\pi*\text{frequency}*L = 2*\pi*1000000*33\text{x}10^{-9} = 0.207\text{ohms}$

$$\text{Accuracy} = \quad 0.10 \ \text{x} \sqrt[\frac{3}{2}]{\frac{1}{1}} \left[\left(1 + \frac{50}{1+10^6} + \frac{10^6}{200k} \right) \left(1 + \frac{|0.207|}{1500} + \frac{1}{|0.207|} \right) \right]$$

Accuracy = 0.1*1[(6.0) * [5.823]] = 3.49%

Example: 1910 Accuracy Graph

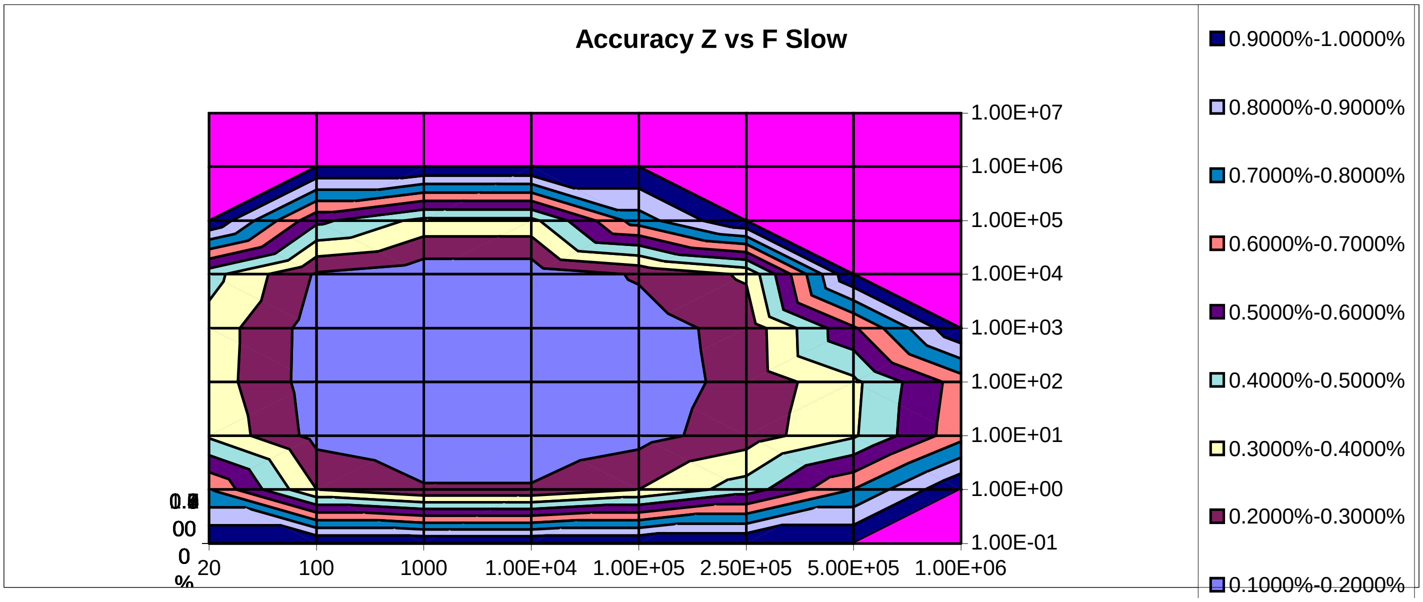
1910 Inductance Analyzer: Graph

The accuracy could not have been accurately determined without the use of a formula. If we calculate the impedance of a 33nH inductor at 1MHz we get a value of:

Z ≈ Xs = 1/(2π*frequency*capacitance)

Z ≈ Xs = (2π*1,000,000*0.000,000,033) = 0.207ohms

Using the graph below and substituting Z for R, we really cannot determine the value other than the error is over 1% which is the maximum value on the graph shown in purple.



1910 Practical Measurement

Figure 3.0 illustrates actual measurements of a 33nH surface mount inductor tested at 1MHz using the 1910 Inductance Analyzer. The inductor was mounted in the 7000-07 Chip Component Fixture. All cables must be fixed as any movement will affect repeatability.

The 33nH inductor had a median value of 34.76nH. Repeatability between consecutive measurements is ±0.2%. The example shows that the repeatability of the measurement is better than the calculated accuracy of ±3.5%.

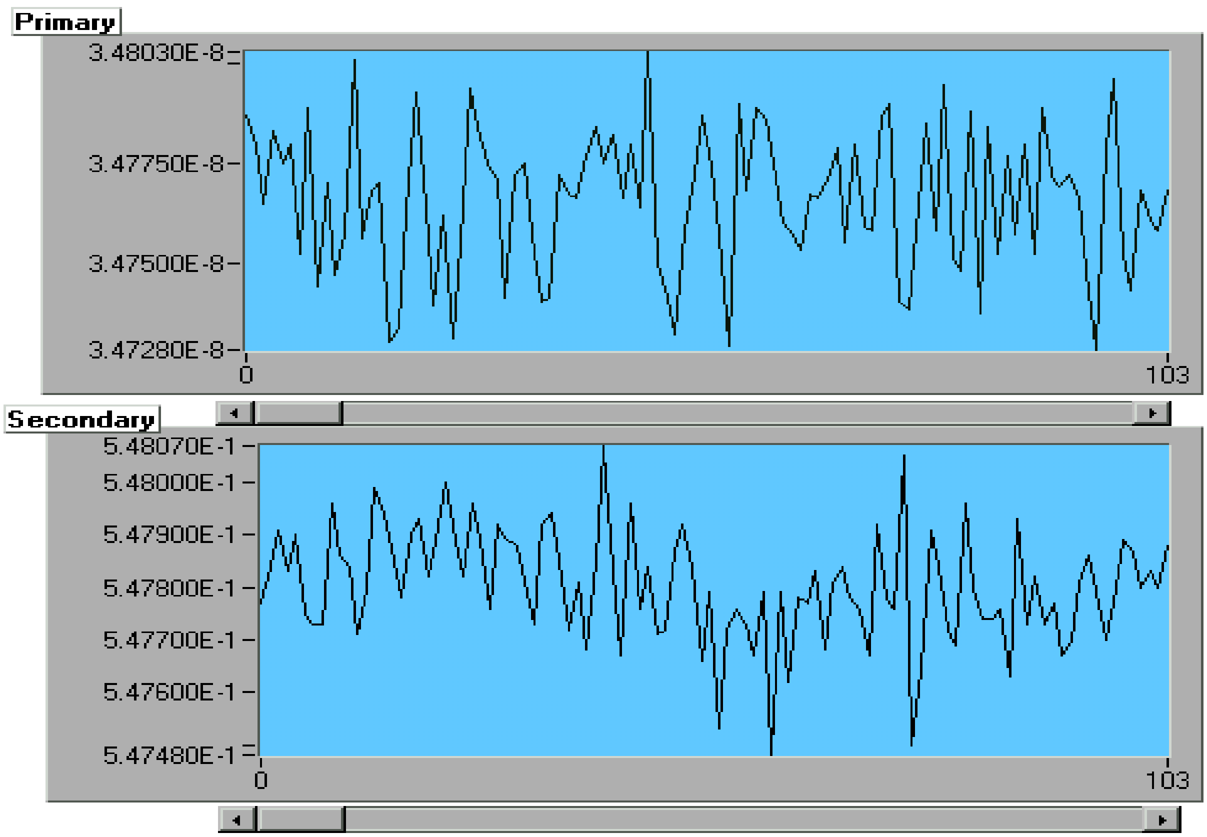


Figure 3.0: Inductance Measurement

For complete product specifications on the 1600, 1900 or 7000 Series 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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