

## LCR Meter Measurement Accuracy

### Introduction

LCR meters make taking L, C and R measurements very easy. One can simply hook up the test component between the clip terminals and get the reading on the display with very little effort. However, if you want to be certain of the measurement that you have made, you must understand how an LCR meter operates and how the component being tested interacts with the meter. It is not uncommon for LCR meter measurements to be off by more than 20% due to the specific test parameters and characteristics of the component being tested. The vector nature of impedance and behavior of series-parallel circuits are keys to making reliably accurate LCR measurements. This application note will provide the theoretical background for measuring impedance and tuning the measurement to improve accuracy.

In real-world applications, loads are neither purely reactive nor purely resistive. However, they can be easily modeled either as a series or parallel combination of a resistive and a reactive load. The equivalent parameter is called *impedance*.

Just as resistance indicates the voltage that will result from a current through a resistor, Impedance is a more general concept of voltage arising from current through generalized complex impedance.

With three “vector” quantities that have different angles defined as:

$$\mathbf{V} = V \angle \psi, \mathbf{I} = I \angle \phi, \mathbf{Z} = Z \angle \theta$$

Then  $\mathbf{V} = \mathbf{I} \cdot \mathbf{Z}$ , which expands into:

$$\mathbf{V} = (IZ) \angle (\phi + \theta)$$

To see that resistance is the special case of  $Z$  where angle is zero, try plugging in zero angle for  $\theta$  above, and note that the voltage rise remains in phase with the current, which is only true for a resistive element.

The following equation expresses impedance in rectangular form:

$$Z = R + jX$$

where,  $R$  and  $X$  are resistance and reactance, respectively. When  $X = 0$ , the load is purely resistive; when  $R = 0$ , the load is purely reactive. At any frequency impedance is either a series or parallel combination of a resistive element and a reactive element which is either capacitive or inductive. Ideal resistive loads exhibit constant impedance regardless of frequency whereas the impedance of reactive loads changes with frequency. In reality all impedances are a combination of resistive and reactive elements referred to as complex impedance

### Understanding the series and parallel circuit

Because components and test loads are not ideal they will be complex impedances. Sometimes an element is so small that it can be effectively ignored and other times it cannot. The typical LCR meter is not able to determine all of the elements that make up a load. It lumps the apparent load into a Thevenized model appearing at the terminals of the meter. Some assumptions are made to accomplish this and understanding these assumptions is essential to making a good measurement. First, let us look at the nature of series and parallel circuits.

The circuits and resulting impedance vector diagrams will look as shown:

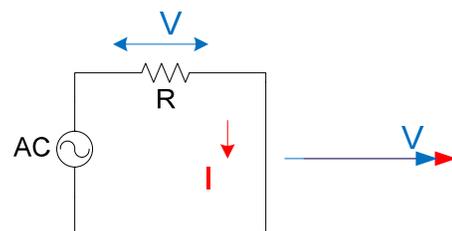


Figure 1 - Pure resistive circuit: Resistor current and voltage are in phase.

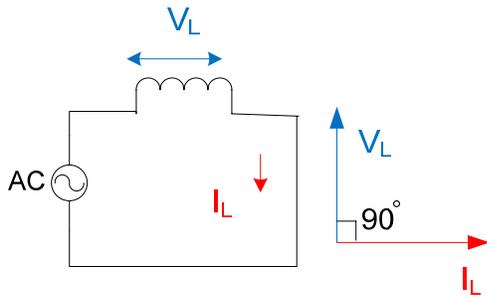


Figure 2 - Pure inductive circuit: Inductor voltage leads inductor current by 90°.

For ideal resistive loads the voltage and current are in phase resulting in an impedance with a phase angle of zero. Purely inductive loads will produce +90 degree phase shifts and purely capacitive loads will produce -90 degree phase shifts. As stated before, real loads do not exhibit ideal characteristics. An example is the common inductor. It is made of many turns of wire that have both significant resistance and inductance. This would appear as Figure 3 to the LCR meter.

Let's take a series-parallel R-L circuit example:

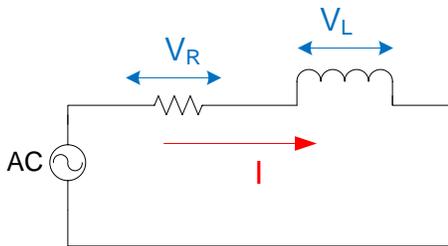


Figure 3 - R-L series circuit

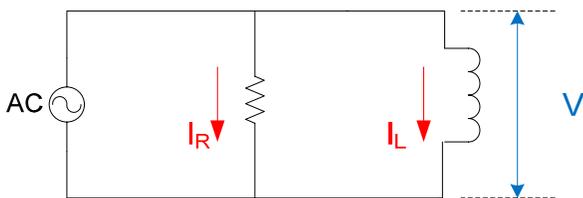


Figure 4 - R-L parallel circuit. Inductor current lags inductor voltage by  $\theta^\circ$ .

In series RL circuits as shown in Figure 3, current always lags the voltage. The current remains the same and voltage gets divided. The total impedance can be written as:

$$Z_{TS} = R + jX_L \quad \text{where } Z_{TS} = \text{total impedance, } R = \text{resistance, } X_L = \text{inductive reactance}$$

Or

$$\bar{Z}_{TS} = \sqrt{(R^2 + X_L^2)} \angle \tan^{-1}\left(\frac{X_L}{R}\right)$$

In the parallel RL circuit as shown in Figure 4, voltage remains constant but current is different. The total impedance can be written as:

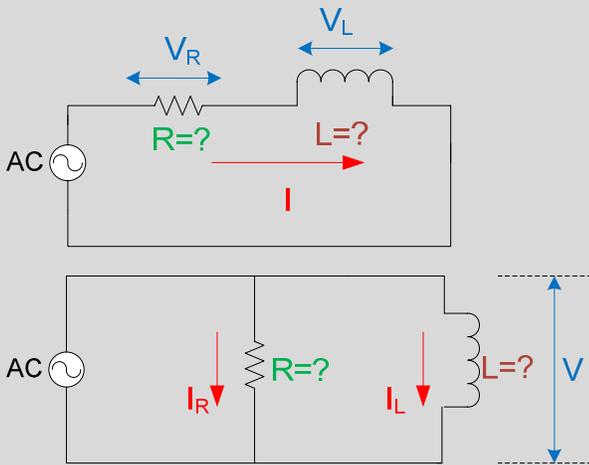
$$Z_{TP} = \frac{R \times (jX_L)}{R + jX_L} = \frac{RX_L^2}{R^2 + X_L^2} + \frac{jR^2X_L}{R^2 + X_L^2}$$

$$\bar{Z}_{TP} = \frac{RX_L}{\sqrt{R^2 + X_L^2}} \angle (90^\circ - \tan^{-1}\left(\frac{X_L}{R}\right))$$

This shows that the value of total impedance changes with the change in the circuit mode even though the same circuit component values are used.

If the measurement is performed while neglecting the circuit modes it is possible to produce a very wrong answer. Different values of resistance and reactance can be combined to produce the same complex impedance.

Example 1



Let the value of Z is  $10.48 \angle 17.43$   
 For series R-L circuit,  
 $Z = R + jX_L$   
 $= 10.48 \angle 17.43 = 10 + 3.14j$   
 Comparing,  
 $R = 10 \Omega$  and  $X_L = 3.14 \Omega$   
 If we take  $f = 50\text{Hz}$ , then  $L = 10\text{mH}$  ---  $X_L = 2\pi f L$

For parallel R-L circuit,  

$$\bar{Z} = \frac{RX_L}{\sqrt{R^2 + X_L^2}} \angle (90^\circ - \tan^{-1}(\frac{X_L}{R}))$$
 $= 10.48 \angle 17.43$  (given)

Solving we get,  $X_L = 3.185 R$   
 Substituting the value of  $X_L$ ,  $10.48 = 0.954 R$   
 $R = 10.98 \Omega$  and  $X_L = 34.98 \Omega$   
 If we take  $f = 50\text{Hz}$ , then  $L = 111.34\text{mH}$

As described earlier, choosing the correct circuit mode is very important; otherwise it may add error to your reading. At times, you may need to obtain the result as a series model or as a parallel model.

In any inductor and capacitor measurement, lead resistance (Rs) and parallel leakage and core losses (Rp) play a vital role in deciding the accurate circuit mode.

To measure small reactive values, such as *high-valued capacitors* as shown in Figure 5 and *low-valued inductors*, it is preferable to use the series model, because the series lead resistance (Rs), although a small value; is more significant than the parallel leakage resistance or core losses (Rp). The series lead resistance becomes more significant at higher frequencies.

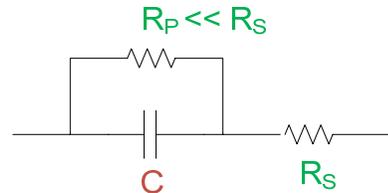


Figure 5 - High-valued capacitor equivalent circuit.

When measuring large reactive values, such as *high-valued inductors* or *low-valued capacitors* as shown in Figure 6, where the capacitor's leakage or the inductor's core losses significantly affects the reading, it is preferable to use the parallel model because the parallel leakage resistance, Rp has a greater effect than the series lead resistance. However be aware that Rs does not go away.

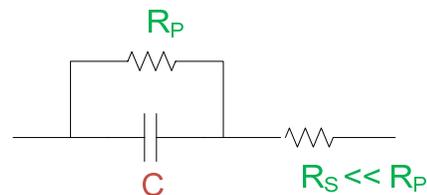


Figure 6 - Low-valued capacitor equivalent circuit.

It is possible to find the value of parallel inductance if the value for series inductance is known and vice versa. Similarly, the value of parallel capacitance can be calculated if the value for series capacitance is known and vice versa. The TEGAM Models 3525 and 3550 have parallel, series and auto circuit modes where the values of the R, L and C in these different modes can be acquired directly for different frequencies.

**Effect on Accuracy**

When doing any impedance measurement with an advanced digital LCR meter, there are some things to keep in mind.

To get a good measurement with any LCR meter, the meter measures the voltage magnitude, the current magnitude, and the phase angle between the current and voltage. If one of the mentioned parameters has poor resolution or poor accuracy, then the measurement accuracy will be seriously degraded. It is also reasonable to note that the ratio between the two magnitudes is very easy to measure because absolute calibration will not be needed; just a linear A/D with a wide range or good attenuators. Measuring the phase is much harder.

In older instruments, analog phase shifters and variable attenuators would be used to feed signals into analog multipliers resulting in signals whose magnitudes represent sin and cos of the phase angle. An arctangent function implemented in analog circuitry would estimate the phase angle. In newer instruments, the coefficients in a Fourier transform are estimated using statistical methods to find the phase angle.

At very low frequencies, zero-crossing detectors and timers may also be used to estimate a measurement of the phase angle.

Clearly, each of the three methods mentioned is more complex and error-prone than computing a magnitude ratio.

**In Summary**

The ratio that gives  $|Z|$  is MUCH MORE ACCURATE than whatever is used to estimate the angle.

Whenever the phase angle is near a multiple of  $\pi/2$ , the uncertainty of one of the values (L/C) or R will be high. For example, suppose you're trying to measure the series R of a winding of a power transformer. Since the angle of Z is nearly 90 degrees, any error in angle will directly cause error in R, whereas the ratio Z is determined nearly completely by  $2\pi fL$ . If the resistance is very small, the meter may even resolve it as a negative number!

The vectors will normally look like Figure 7 when the LCR meter is able to resolve all three parameters accurately. In this case a good measurement can be made because there is a substantial V and I component with sufficient phase angle between them. If one of these three components were to decrease substantially then the meter may not be able to produce an accurate reading.

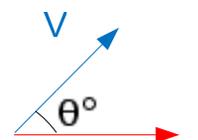


Figure 7 - V-I vector diagram.

An LCR meter functions by applying either a constant voltage and measuring the resulting current or by applying a constant current and measuring the resultant voltage. There are three measurement modes in the TEGAM 3550; namely open circuit test voltage mode, constant voltage measurement mode and constant current measurement mode. For ordinary test objects that possess average impedance use the open circuit voltage mode. For more stable readings it is best to test inductors in constant voltage mode and capacitors in the constant current mode.

When measuring really high impedances (in  $M\Omega$ ) or really low impedances (in  $m\Omega$ ), the accuracy gets largely affected because one of the signals (V or I) is very small and therefore difficult for the LCR meter to measure. Let's consider some examples:

Case 1- Measuring very large impedance:

We know that,  $V = I * Z$ . If we keep the voltage constant, as the impedance (Z) increases the current (I) decreases. The vector diagram will look like this:

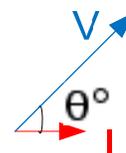


Figure 8 - V-I vector diagram when measuring very large impedance.

In this case the value of I is very low; thus affecting the instrument's accuracy.

Case 2- Measuring very low impedance:

$$V = I * Z,$$

If we keep the current constant, as the impedance (Z) decreases the voltage (V) decreases.

But in this case the value of V is very small which affects the measurement accuracy. The vector diagram will look like this:

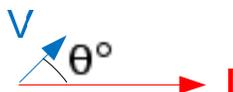


Figure 9 - V-I vector diagram when measuring very low impedance.

In summary, since the magnitude of the complex impedance presented by a test load varies with frequency, the LCR meter can be tuned to improve the measurement. Adjusting the frequency that the measurement is taken at can significantly improve the accuracy by putting the voltage and current vectors into a better measurement range. LCR meters typically come with extensive tables that the user can apply to calculate accuracy. This can be a very tedious process and should only be undertaken by the experienced user. TEGAM has simplified this process for our Model 3550 with a spreadsheet that automatically calculates the measurement accuracy based on the expected impedance and measurement parameters. This allows a user to determine what accuracy can be achieved and adjust the parameters to improve the accuracy prior to purchasing an instrument. The spreadsheet is available at <http://www.tegam.com/html/3550.htm>.

**TEGAM LCR Meter Products**

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|--|---|
|  <p>The Model 3550 42.0 Hz to 5.00 MHz Programmable Impedance/LCR Meter offers the best cost/performance value on the market.</p>    | <ul style="list-style-type: none"> <li>★ User-selectable test frequency from 42.0 Hz to 5.00 MHz</li> <li>★ 18 mS measurement speed</li> <li>★ 0.10% basic accuracy</li> <li>★ Fully programmable</li> <li>★ 18 measurable parameters</li> <li>★ Absolute or percentage comparator</li> <li>★ Binning function supports 10 output bins</li> <li>★ 3 highly-visible LED displays</li> <li>★ Standard RS-232C &amp; I/O interfaces</li> <li>★ Optional GPIB or BCD interfaces</li> <li>★ 1-year warranty</li> </ul>   |
|  <p>The Model 3525 High Accuracy, 1 kHz/120 Hz, Programmable Impedance/LCR Meter offers high performance testing at a low cost.</p> | <ul style="list-style-type: none"> <li>★ 0.08% basic accuracy</li> <li>★ 1 kHz or 120 Hz test frequencies</li> <li>★ Fast measurement speed (15 mS)</li> <li>★ Extremely compact size (8" w x 4" h x 7" d)</li> <li>★ Simple to use</li> <li>★ Manual or automated operation</li> <li>★ Better than Agilent at half the price</li> <li>★ 99 storable panel settings</li> <li>★ Built-in comparator with external buzzer</li> <li>★ Highly-visible dual 4.5 digit LED displays</li> <li>★ Voltage &amp; current monitors</li> <li>★ Standard RS-232C &amp; I/O interfaces</li> <li>★ Optional GPIB or BCD interfaces</li> <li>★ 3-year warranty</li> <li>★ Kelvin Klips and calibration certificate</li> </ul> |