

LCR Meter

Guide

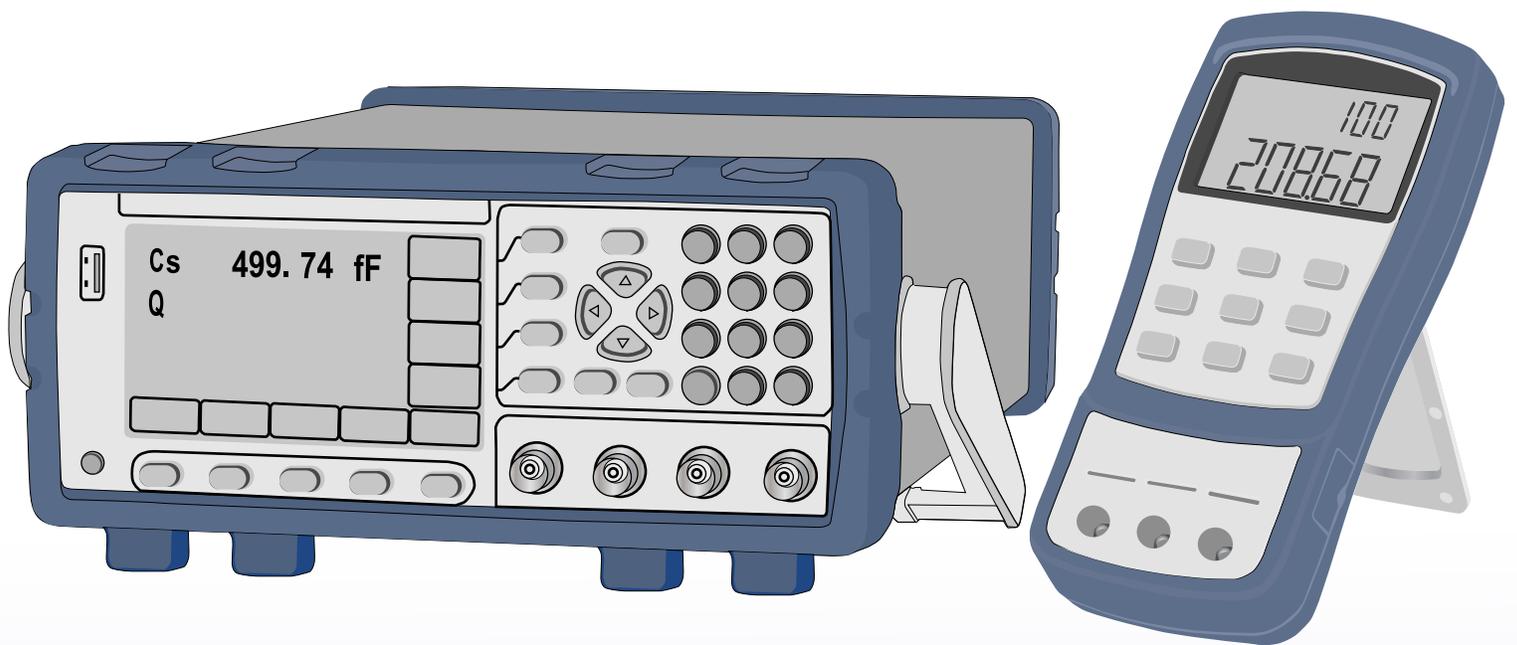


Table of Contents

Introduction	4
What is an LCR meter?	4
Benefits of an LCR meter	4
Example applications	5
Constructing an RC filter	5
Characterizing an induction motor	5
Impedance	7
The physical nature of reactance	10
Dissipation factor D and quality factor Q	12
Lumped parameter models	12
Series and parallel models	14
Should I use the series or parallel model?	15
Measurement of impedance with an oscilloscope	16
Bridge circuits	19
Some formulas related to impedance	20
Capacitance	21
Inductance	22
Using a reactance chart	23
LCR Meter Features	25
Meter types	25
Selectable test frequencies	25
Selectable test amplitudes	26
Relative mode	26
Tolerance mode	27
4-wire measurements	27
ESR measurements	28
Connectivity	28
Voltage and current measurements	29
Lead slots and surface mount tweezers	30
Making LCR Measurements	31
Safety	31
Test frequency	31
Open/short calibration	31
2-, 3-, and 4-wire measurements	34
2-wire measurements	34
3-wire measurements and guarding	35
4-wire measurements	36
Range and accuracy of LCR meters	36
Measurement uncertainty	37
Measurement standards	37
Measurement discrepancies	38
Good practices	40
FAQ	43
What is admittance?	43
Why do I get a negative reading?	43

A motor measurement example	43
Why can't I get a stable reading?	45
This inductance doesn't measure correctly	46
This capacitor is too large to measure	46
Glossary and symbols	47
References	49

Introduction

What is an LCR meter?

An LCR meter is an electrical test instrument used to measure inductance (L), capacitance (C), and resistance (R) of components and circuits at various frequencies. Besides displaying these electrical characteristics, LCR meters can also typically display impedance (Z), phase angle (θ), dissipation factor (D), quality factor (Q), and equivalent series resistance (ESR). Some LCR meters display admittance and its components, conductance and susceptance.

The LCR meter measures the impedance of the component or circuit at its terminals. This is usually done by applying a sinusoidal waveform at a specified frequency and measuring the resulting sinusoidal current along with the phase difference between the applied voltage and resulting current. The meter then calculates the impedance from these measurements. Other electrical characteristics can be calculated from the components of the impedance.

As electrical components and circuits come in a variety of forms, various leads and fixtures are needed in conjunction with the LCR meter to allow a physical connection between the device under test (DUT) and the LCR meter. As these leads/fixtures also have impedance, it is important to compensate for them to know the true impedance of the DUT.

Benefits of an LCR meter

It is likely that once you become comfortable making measurements with an LCR meter, you will find many applications for it. An LCR meter is a powerful adjunct to a digital multimeter. The following are some benefits of an LCR meter:

- Measure the impedance of a circuit and help you troubleshoot or characterize existing circuits.
- Identify unmarked components and sort components into bins with specified tolerances.
- Battery-operated, handheld LCR meters are convenient to carry into the field for testing away from the bench.
- Measure AC characteristics of a component as a function of frequency and amplitude to help you predict the AC behavior in a circuit.
- Characterize motors¹ by inductance measurements and inductance as a function of rotor angle.
- Identify the coil leads of an unmarked relay by measuring the inductance.
- Select components for passive filters, then measure the filter's impedance at various frequencies.
- Measure components in-circuit. In particular, find capacitors with high ESR.
- Estimate the winding ratio of a transformer via inductance measurements.
- Measure the Q of coils. Sometimes a lossy inductor is desired and the LCR meter can tell you if you've made it correctly.
- If you maintain equipment, measure the equipments' characteristics with the LCR meter and write the values down for future reference.

¹ Be careful with permanent magnet motors as they could generate a DC voltage that could damage your LCR meter.

Example applications

Constructing an RC filter

Suppose an application needs an RC filter with a time constant of 450 μs and we want the filter's time constant to be within 1% of the desired value. We pick a nominal resistance R of 1 $\text{k}\Omega$. Then, we calculate the needed capacitance as:

$$C = \frac{t}{R} = \frac{450 \mu\text{s}}{10^3 \Omega} = 450 \text{ pF}$$

However, we don't have any 450 pF capacitors on-hand. We use the LCR meter to check some capacitors we do have on-hand and find a capacitor with a parallel model capacitance of 126.6 pF at a test frequency of 1 kHz.

Substituting 126.6 pF into $R = t/C$, we find we need a 3.55 $\text{k}\Omega$ resistor to achieve the desired time constant. We check our resistor stock and find that we can use some 1.18 $\text{k}\Omega$ and 2.37 $\text{k}\Omega$ resistors we have on-hand to get the exact value by connecting them in series. We use the LCR meter to measure the AC resistance of some of these resistors and find a pair of them that give the desired series resistance. The resulting RC filter will then have the desired time constant.

The LCR meter allows these measurements to be made quickly, so the overall task of finding suitable components can be done quickly and without fuss.

Characterizing an induction motor

A new industrial installation includes a 3-phase induction motor. Because the motor must run reliably to support a plant that runs 24 hours per day and 7 days per week, the maintenance technicians decide to characterize the motor's electrical characteristics so they have the measurements in their records for future troubleshooting and maintenance tasks.

A technician uses an LCR meter to measure the inductance of the three windings at a test frequency near the line frequency. Later, a motor fault such as a shorted winding in one of the motor's poles can be diagnosed by the resulting change in the inductance. The maintenance department could make it a policy to measure the winding inductances on a periodic basis -- it requires minimal downtime and can help diagnose potential degradation in the windings.

The technician, however, goes further with his diagnostic check and performs a **rotor influence check**, which involves measuring each winding's inductance as a function of rotor angle. Plotting the inductance of each of the three windings as a function of angle can uncover subtle issues with the motor's overall health.

For multi-phase induction motors, comparing the inductance of the stator's windings may help diagnose problems. Figure 1 schematically illustrates the effects of a shorted turn in a single winding of the stator of a 3-phase motor.

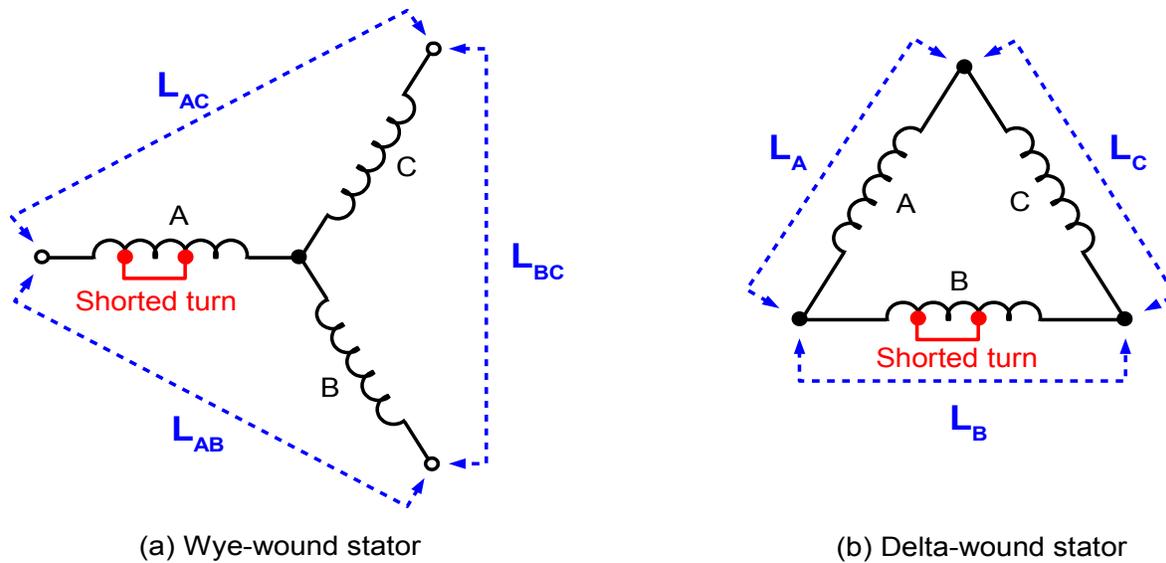


Figure 1: Three-phase shorted turn inductances

For a new motor, the inductance of the three windings should be approximately equal. A useful strategy is to measure the winding(s) when the motor is new and have those measurements for comparison to later measurements when troubleshooting a problem or looking for degradation. Measuring a good winding's inductance on a new motor also lets you use the change in inductance to troubleshoot a single phase motor in the future. You'd also want to measure and record the inductance periodically.

A shorted turn will have a lower inductance than an equivalent non-shortened turn. Thus, we have the following relationships for a motor with a shorted turn:

Wye	$L_{AC} \approx L_{AB} < L_{BC}$
Delta	$L_B < L_A \approx L_C$

For the wye connection, we also have the relationships:

$$L_{AB} = L_A + L_B$$

$$L_{AC} = L_A + L_C$$

$$L_{BC} = L_B + L_C$$

If you measured the phase-to-phase inductances for a wye-connected motor and found that two of the inductances were about equal and less than the third, you'd suspect a shorted turn. For a delta-connected motor, you'd suspect a shorted turn if one of the inductances was less than the other two, which should be nearly equal. One metric is to calculate the mean inductance and then examine the % deviation from the mean to identify an inductive imbalance.

Shorted turns can occur when the insulation in a winding fails to insulate the winding wire sufficiently (i.e. hot spots, physical damage, manufacturing defect, etc.).

Impedance

The concept of impedance is central to the use and interpretation of the measurements made by LCR meters. This section summarizes the basic principles of electrical impedance. For more technical details, consult a text on beginning circuit theory.

The definition of resistance of a circuit element is the DC voltage across the component divided by the DC current through the component. Note that resistance is a DC parameter. When the voltage is varying (i.e., "AC"), things are more complicated.

We want to continue to utilize the idea that opposition to current flow is defined by the voltage divided by the current (i.e., a particular circuit takes a certain number of volts to get 1 ampere of current). However, capacitors and inductors are components that can store electrical energy. This storage capability leads to a situation where the **current and voltage are out of phase**. It turns out that the algebra of complex numbers provides a good model of the AC behavior because the amplitude and phase behaviors can be accommodated.

The ideas used in the modeling of these AC situations are:

1. The discussion will be restricted to the behavior of **sinusoids** at one frequency².
2. We will only look at the steady state situation (i.e., after transient behaviors from switch closures, etc. have died out).
3. There are two independent physical parameters that characterize the sinusoid: **amplitude** and **phase**.

Resistance is generalized to impedance using the definition:

$$Z = \frac{V}{i}$$

where now the voltage **V** and current **i** are sinusoids at a specified frequency. These sinusoids are represented by complex numbers called **phasors**, discussed in more detail below.

An arbitrary sinusoidal voltage as a function of time can be represented by the function:

$$V(t) = V_0 \cos(\omega t + \delta) \quad (1)$$

where

t = time in seconds

V_0 = the zero-to-peak amplitude of the sinusoid (a constant) in volts

ω = angular frequency of the sinusoid in radians/seconds = $2\pi f$ where f is the frequency in Hz

δ = the phase of the waveform in radians

Since we are talking about sinusoids, you might think you should see the sine function in this formula, but a practical detail given below makes using cosines more convenient. The phase δ is relative to some particular sinusoid at the same frequency that is defined to have a phase of zero.

The machinery of complex numbers describes these sinusoids by virtue of **Euler's formula**, one of the most useful relationships in mathematics:

$$e^{x+jy} = e^x(\cos y + j \sin y) \quad (2)$$

A reason why this formula is so useful in discussing impedance is that **multiplication and division of complex numbers can be done by adding exponents**. We will be calculating the impedance by dividing two complex numbers.

2 More general waveforms and responses are handled using Fourier series and integrals.

The benefit of using complex numbers is that the solution of linear time-invariant differential equations can utilize the algebra of complex numbers instead of analytical methods for solving differential equations. This is a feature of transforms such as the Laplace transform. Transforms can replace the more difficult task of solving a differential equation by transforming to a "space" where the solution is affected by algebraic techniques. A useful observation is that phasor voltages and currents satisfy Kirchoff's laws, which are expressions of the conservation of energy and charge.

Using Euler's formula, we can represent a general sinusoid by the expression:

$$V(t) = \underbrace{V_0 e^{j\delta}}_{\text{phasor}} e^{j\omega t} \tag{3}$$

The convention is to use the real part of equation (3) to give the sinusoidal function of time. The real part is $V_0 \cos(\omega t + \delta)$, i.e., equation (1). This is why the cosine is used for the sinusoid instead of the sine. A cosine curve is a sine that is shifted by a right angle.

Combining the exponents, using Euler's formula, and taking the real part results in the sinusoid function given in equation (1), **the phasor is a time-independent complex constant that encodes the amplitude and phase information of the sinusoidal voltage**. As the $e^{j\omega t}$ term is common to each sinusoid, we can combine sinusoids via addition, subtraction, multiplication, and division using phasors and/or Euler's formula.

For example, the addition of two sinusoid voltages of angular frequency ω , amplitudes V_1 and V_2 , and phases δ_1 and δ_2 is:

$$V(t) = \underbrace{(V_1 e^{j\delta_1})}_{V_1} + \underbrace{(V_2 e^{j\delta_2})}_{V_2} e^{j\omega t} = \underbrace{V_{\text{sum}} e^{j\mu}}_V e^{j\omega t}$$

Note that the time-dependent part can be ignored as long as we remember these phasor relationships are always associated with the implicit frequency ω . Then the resulting phasor V is the sum of the two phasors V_1 and V_2 . This is just addition of two complex numbers, which you would calculate by converting to rectangular components and adding the corresponding components. This is the same as vector addition in the two-dimensional Cartesian plane, which is why phasors are sometimes called vectors.

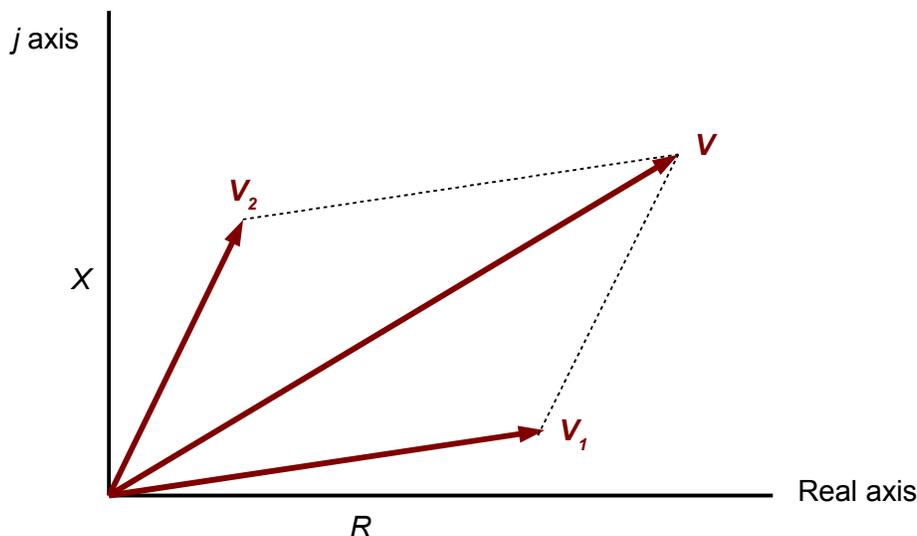


Figure 2: Sum of two phasors

This proves that the sum of two arbitrary sinusoids of the same frequency, but different amplitudes and phases, is another sinusoid of the same frequency. The proof using trigonometric identities is more involved³. The resultant phasor is the sum of two complex numbers.

Note a phasor is a constant complex number. When multiplied by the $e^{j\omega t}$ term to convert it to the actual sinusoid as a function of time, the $e^{j\omega t}$ term can be interpreted as a rotating unit vector. Thus, a sinusoid $V e^{j\omega t}$ is sometimes called a rotating vector.

Since impedance is defined as the ratio of a voltage sinusoid to a current sinusoid at the same frequency, we can write:

$$\mathbf{Z} = \frac{V(t)}{i(t)} = \frac{V_0 e^{j\delta_v} e^{j\omega t}}{i_0 e^{j\delta_i} e^{j\omega t}} = \frac{V_0}{i_0} e^{j\theta} = Z e^{j\theta}$$

Note that **impedance is a phasor**, as the time dependence has canceled out⁴.

Two observations are:

1. The magnitude of the impedance $|\mathbf{Z}| = Z = V_0/i_0$ is the magnitude of the voltage divided by the magnitude of the current. Mathematically, magnitudes are the 0-to-peak value of a sinusoid. However, you can use RMS value, peak-to-peak value, average value, etc. for calculating the impedance as long as the particular measure is used for both current and voltage, and the measure is proportional to the 0-to-peak value.
2. The phase difference $\theta = \delta_v - \delta_i$ between the voltage and current is what's important in the impedance. In the **Measurement of impedance with an oscilloscope** section, an example is given showing an oscilloscope measuring this phase difference.

As an example of where the time dependence $e^{j\omega t}$ cannot be ignored, calculate the instantaneous power waveform for a sinusoidal current and voltage at the same frequency. Note the frequency of the power waveform.

Using Euler's formula (2), we can write down the rectangular form of the impedance:

$$\mathbf{Z} = |\mathbf{Z}| \cos \theta + j|\mathbf{Z}| \sin \theta = R + jX \quad (4)$$

where R is a resistance and X is a **reactance**. These two numbers are the Cartesian components of the impedance and can be related to the parallel and series models' equations given in the section, **Some formulas related to impedance**. The polar representation of an impedance phasor using $|\mathbf{Z}|$ and θ are related to the rectangular coordinates of resistance R and reactance X through the following diagram:

³ Euler's formula can be used to economically prove many trigonometric identities.

⁴ This result is only true for linear time-invariant systems, which describes many situations of practical interest.

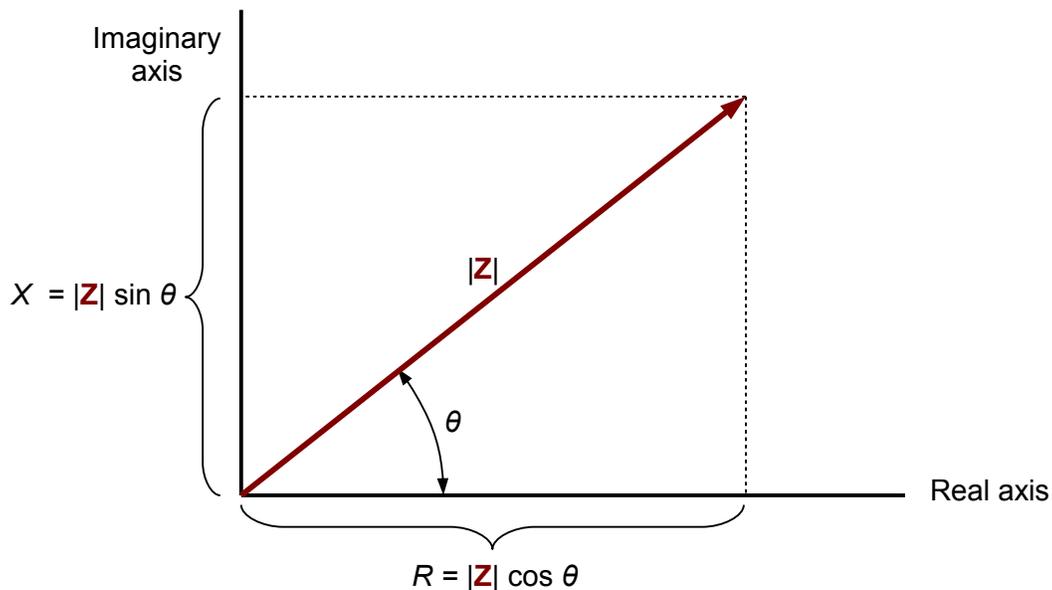


Figure 3: Complex impedance plane

It must be emphasized again that this complex impedance is a phasor and must always be given with the frequency it is measured at. If the frequency changes, the impedance will generally change.

The typical LCR meter measures the magnitude $|Z|$ and phase angle θ directly, which lets you utilize equation (4) for subsequent calculations. The equations let us write down the expressions for the reactances of inductors and capacitors:

$$\begin{aligned} X_L &= \omega L \\ X_C &= \frac{1}{\omega C} \end{aligned} \tag{5}$$

The impedance magnitude $Z = |Z|$ is important because it determines the magnitude of the current flow when given a particular voltage: $i = V/Z$. The phase of the impedance determines the phase relationship between the voltage and current, and also determines the real power dissipated in the circuit. The utility of impedance is the same as resistance, as the formulation and mathematics allow series impedances to add algebraically and parallel impedances to add in the same way parallel resistors do. Thus, steady state AC analysis is much like DC circuit analysis, except that it is at a particular frequency and there can be arbitrary phases involved.

Impedance-related calculations are more convenient with a calculator or computer program that can perform complex number calculations in both rectangular and polar coordinates.

The physical nature of reactance

For an uncharged capacitor, the initial resistance to a charging current is low, meaning the initial charging current is high. As the charge on the capacitor increases, the electrostatic forces increasingly repel the accumulation of more charge, lowering the current through the capacitor. Thus, the current is high when the voltage is low and the current decreases as the voltage increases. Thus, the current through a capacitor leads the voltage across the capacitor.

At high frequencies, the current flows for only a short period of time before the applied voltage changes polarity. Thus, there is little opposition to the current from the accumulated electrostatic charge. This explains why the **capacitive reactance decreases with increasing frequency**.

Because the definition of capacitance is $Q = CV$ and the charge on the capacitor is the time integral of the current through the capacitor, the instantaneous voltage on a capacitor is:

$$V(t) = \frac{1}{C} \int_0^T i(t) dt$$

At high frequencies, the integration time T is a small number, which causes the integral to be a small number. The voltage across the capacitor is thus small and this is the characteristic of a short.

At DC, the capacitor draws current until it is charged to the same potential as the voltage source, then the electrostatic field on the capacitor stops any further current flow.

We can conclude:

- ◆ The current through a capacitor leads the voltage across the capacitor.
- ◆ Capacitors look like shorts at high frequencies.
- ◆ Capacitors look like open circuits at frequencies near zero.

The situation is different for an inductor. The voltage across the inductor is proportional to the time rate of change of the current through the inductor:

$$V(t) = L \frac{di}{dt} \quad (6)$$

Suppose the current through an inductor is a sinusoid of angular frequency ω :

$$i = i_0 e^{j\omega t}$$

where we have emphasized that the current is a phasor, but defined the phase to be zero. Then,

$$\frac{di}{dt} = i_0 j \omega e^{j\omega t} = i_0 \omega e^{j\frac{\pi}{2}} e^{j\omega t}$$

$j = \exp(j\pi/2)$, so equation (6) becomes:

$$V(t) = \mathbf{V} e^{j\omega t} = \underbrace{L i_0 \omega e^{j\frac{\pi}{2}}}_{\text{voltage phasor}} e^{j\omega t} \quad (7)$$

Because of the phasor term, you can see the voltage across an inductor leads the current by 90° and the voltage's frequency-dependent magnitude is $L i_0 \omega$.

The inductor's impedance from the definition of impedance as the ratio of the voltage to current is:

$$\mathbf{Z}_L = \frac{\mathbf{V}}{\mathbf{i}} = L \omega e^{j\frac{\pi}{2}} \quad (8)$$

Since this is an ideal inductor with no DC resistance, the reactance (imaginary part of the impedance) increases linearly with frequency. A pure inductor's impedance has a phase angle of $+90^\circ$.

At low frequencies, the impedance magnitude is numerically small, so the inductor behaves like a short. As the frequency increases, the voltage across the inductor increases. If you can make the current change rapidly enough, you can get any desired instantaneous voltage across the inductor. This is the cause of inductive voltage spikes.

We can conclude:

- ◆ Voltage across an inductor leads the current through the inductor.
- ◆ Inductors look like shorts at low frequencies.
- ◆ Inductors look like open circuits at high frequencies.

Mathematically, the leading and lagging of the voltage vs. current in capacitors and inductors come about because the integral and derivative of a sinusoid are both sinusoids, but shifted by $\pm 90^\circ$. Alternatively, you can do the experiment in the section, **Measurement of impedance with an oscilloscope** to demonstrate this fact experimentally.

Dissipation factor D and quality factor Q

The dissipation factor D is a dimensionless quantity representing the ratio of the real part of the impedance to the imaginary part.

$$D = \frac{R}{X} \quad \text{where} \quad \mathbf{Z} = R + jX$$

"Pure" components have low values of D . Here, "pure" means the impedance has a small real part. For a capacitor, the dissipation factor D relates the series model's capacitance C_s to the parallel model's capacitance C_p :

$$C_s = C_p(1 + D^2)$$

For values of D near zero, you can see that C_s and C_p are nearly equal. The series and parallel capacitances are equal to within 0.1% when D is less than 0.032.

From equation (14), we have for the series model that:

$$R_s = \text{ESR} = \text{equivalent series resistance} = \frac{D}{\omega C_s}$$

For a fixed frequency and the series capacitance model, the equivalent series resistance is small when D is small. As the ESR dissipates real power in a circuit, a small ESR is desirable for efficiency, so capacitors with low D are desirable, especially in power circuitry. Physically, there is no resistance in series with a pure capacitor; the ESR is an abstraction representing the complicated distributed behavior of leakage, dielectric losses, lead resistance, and other physical effects.

For inductors, it is conventional to use the quality factor Q , which is the reciprocal of D . High- Q inductors are often desired. From equation (15), we have for the series model that:

$$R_s = \text{ESR} = \frac{\omega L_s}{Q}$$

Thus, a high- Q inductor has low equivalent series resistance and loses little power to this ESR.

High- Q and low- D components can be desirable in circuitry because they can allow efficient transfer of energy between capacitors and inductors in resonant circuits, and efficiently store energy with little loss to waste heat. D for a capacitor will typically rise nonlinearly with frequency and temperature.

When using an LCR meter to measure D for a component that is nearly a pure reactance, D can be a small number, perhaps in the range of 0.0001 to 0.0010. Since Q is the reciprocal of D , you can have the meter display Q instead and take the reciprocal to get more significant figures in the measurement of D .

Lumped parameter models

Imagine you want to measure the capacitance of a piece of coaxial cable. A model can be constructed of the measurement situation as follows. The cable is divided into many small identical chunks connected in parallel, each with its own capacitance.

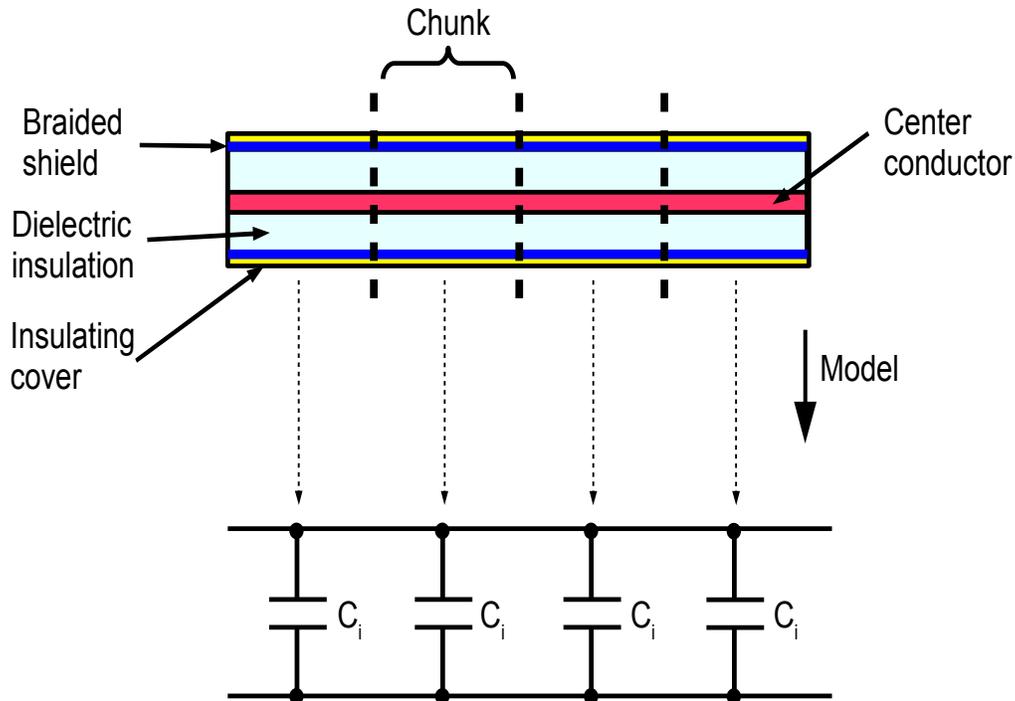


Figure 4: Capacitance model of a coaxial cable

Each small chunk of cable contributes a capacitance C_i . Since parallel capacitors add their capacitances to get the total capacitance, the capacitance of the cable is the sum of the individual capacitances. We then have a model of the cable's capacitance, which is just a single capacitor. We have lumped the contribution of many small components into a single component. This leads to the concept of a **lumped parameter model**. The engineering simplification is that a complicated physical system can be adequately represented by a circuit of discrete components, which in turn can be represented by a single component. In other words, the complicated system is replaced by something simpler that behaves in a similar fashion.

It has been shown by long experience that lumped parameter models work in a variety of situations, as evidenced by the use of circuit theory in modeling the behavior of complicated components and collections of components that would be impractical to model using the full machinery of electromagnetic theory. Trying to predict the behavior of all the components of a radio using Maxwell's equations would be a virtually impossible task. However, using judicious approximations and lumped parameter models, an engineer is able to predict the behavior of a radio sufficiently well for design and production needs.

In some situations, more complicated lumped parameter models may be appropriate. For example, here is a model that includes a capacitor's ESR (R_s), lead inductance, insulation resistance, and dielectric absorption (DA):

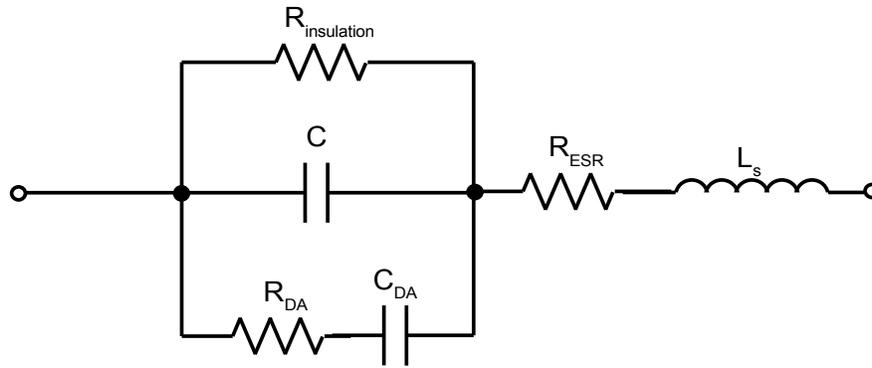


Figure 5: Example lumped parameter model of a capacitor

The suitability of this model would have to be established empirically and the effort to measure each of the contributing factors of the model could be significant.

The series and parallel circuits measured by LCR meters are lumped parameter models of a measured impedance.

Series and parallel models

Two common lumped parameter models for the impedance of real-world components are the series and parallel models. These model the component's measured impedance by an ideal resistance and an ideal reactance in series or parallel.

They are:

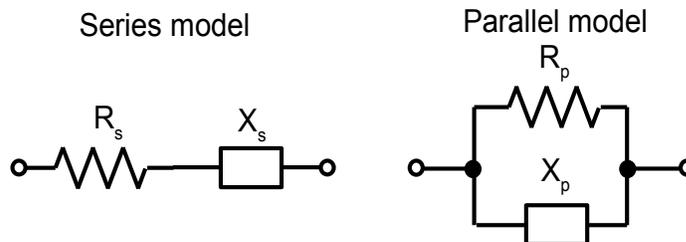


Figure 6: Series and parallel models

The impedance for the series model is:

$$\mathbf{Z} = R_s + j X_s \quad (9)$$

The impedance for the parallel model is:

$$\frac{1}{\mathbf{Z}} = \frac{1}{R_p} + \frac{1}{j X_p} \quad (10)$$

If you do the algebra on equation (10) to get an expression for \mathbf{Z} , you can equate the real and imaginary parts to equation (9) and derive the relationships between the models' component values as given in equations (14) and (15).

These circuit models are mathematically equivalent. The LCR meter measures an impedance, which gives two independent numbers, the magnitude and phase of the impedance. These are changed into rectangular components R and X , giving the real and imaginary part of the impedance. These rectangular components can then be transformed into either a series or parallel circuit of a pure resistance and a pure reactance. These transformed circuits have exactly the same impedance as the measured value, but this is true only at the measured frequency. The sensitivity or uncertainty of

the LCR meter may be different for the numbers given by the two different models, so consult the user's manual to help make decisions about measurement details.

Should I use the series or parallel model?

Assuming frequencies are low enough so that lead inductance is not important, one possible model of an impedance would be a combined series/parallel model:

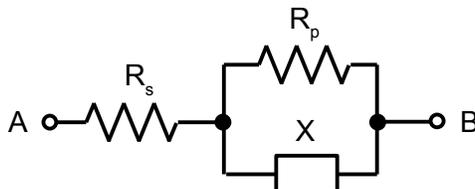


Figure 7: Combined series/parallel model

Imagine this model is for a capacitor. The series resistance R_s represents a resistance that results in power losses and is a relatively low resistance. The parallel resistance R_p represents leakage and can be a relatively high resistance. For large filter capacitors, R_s can be in the milliohms range. Since these large capacitances also have low reactances, it makes sense to consider the series model and ignore R_p because R_p will not sensibly contribute to the normal circuit behavior as the low resistance/reactance will swamp it out. The real part of the impedance will be the ESR, which is R_s . For small capacitors, we are not much interested in any power dissipated in the equivalent series resistor, but leakage may be more important as the capacitor is often used to store charge. For this case, the parallel model is more appropriate because the resistor R_p models a leakage current that "goes around" the pure capacitance.

To measure the impedance of this equivalent circuit, you need to put a sinusoidal voltage across terminals A and B and measure the current through the circuit. For a low reactance part, the overall impedance will be relatively small and the current will be straightforward to measure because it will have a reasonable amplitude. However, if the reactance is large (i.e. a small capacitor or large inductance), the result is a small current, which can be more challenging to measure. The measurement can have higher noise, leading to more uncertainty.

For inductors, the parallel model is used for large inductors and the series model for small inductors. The series model is convenient when the inductor has a significant DC resistance; R_s is also called ESR (equivalent series resistance) for inductors. The parallel model can be thought of as using the resistance R_p to model ferromagnetic core losses.

These guidelines can be summarized in an approximate rule:

Use the parallel model when the reactance is greater than 100 Ω . Use the series model when the reactance is less than 100 Ω .

The following table translates this approximate rule into inductance and capacitance values:

Frequency (kHz)	Capacitors		Inductors	
	Use series model when	Use parallel model when	Use series model when	Use parallel model when
0.1	> 16 μF	< 16 μF	< 160 mH	> 160 mH
1	> 1.6 μF	< 1.6 μF	< 16 mH	> 16 mH
10	> 160 nF	< 160 nF	< 1.6 mH	> 1.6 mH
100	> 16 nF	< 16 nF	< 160 μH	> 160 μH
1000	> 1.6 nF	< 1.6 nF	< 16 μH	> 16 μH

Table 1: Series/parallel model guidelines

Measurement of impedance with an oscilloscope

In this section, we look at using an oscilloscope to measure the impedance of a device. The method uses the definition of impedance as a complex voltage divided by a complex current at a given frequency and reflects the way modern LCR meters often make their measurements. If you have an oscilloscope and a function generator, you can perform this experiment yourself.

The experiment's objective is to measure the impedance of a capacitor or an inductor. For this example, we will use a capacitor and the measurement circuit is as follows:

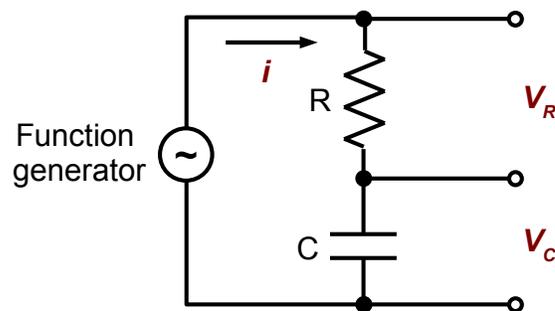


Figure 8: Impedance measurement circuit

The experiment will set the function generator to a sine wave at a desired measurement frequency and use the oscilloscope to measure the voltages V_R and V_C across the resistor and capacitor, respectively. The resistor is in the circuit to allow us to infer the current i from the voltage across the resistor. This resistor should be non-reactive at the measurement frequency. Remember that V_R , V_C , and i are phasors. If you have a suitable current probe, you can eliminate the resistor.

To calculate the impedance of the capacitor, we need to measure three numbers:

1. V_R = the amplitude of the sinusoidal voltage across the resistor.
2. V_C = the amplitude of the sinusoidal voltage across the capacitor.
3. δ = the phase difference between the voltages V_R and V_C .

A measurement complication is that function generators and oscilloscopes typically have their inputs and outputs referenced to ground for safety reasons. This makes it a little more challenging to measure the voltages V_R and V_C . Two possible measurement methods are to isolate the function generator's output with a small transformer or use differential amplifiers to measure the voltages across the components.

Here, we'll use a small transformer⁵ to isolate the function generator's output. We also show the oscilloscope connections we'll make:

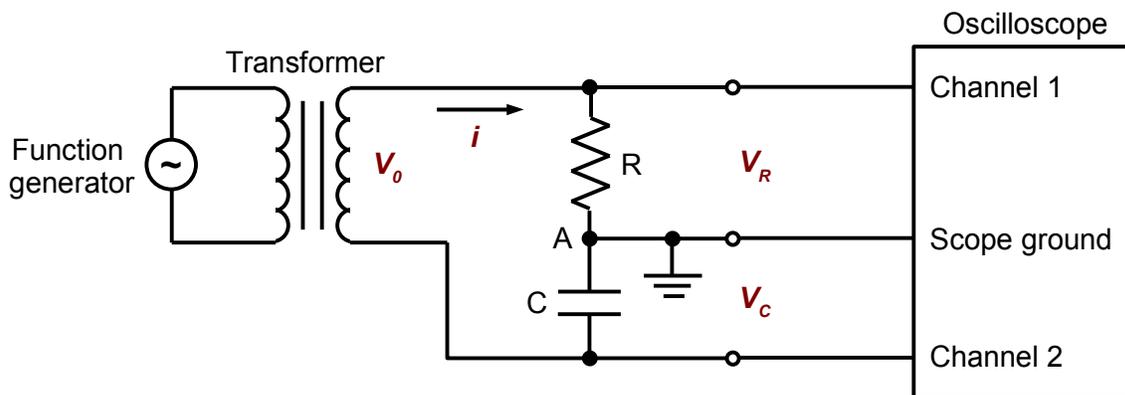


Figure 9: Oscilloscope connections

Because of the connection topology (note point A is at measurement ground potential), the voltage V_C measured across the capacitor will be inverted from the voltage we want to measure. This can be corrected by inverting either channel 1 or channel 2. Once this inversion is done, both waveforms can be displayed on the scope's screen at the same time and you can measure the phase difference δ between the sinusoids.

Using a 100 nF nominal capacitor and a 1 k Ω resistor (which had a measured DC resistance of 978 Ω) with a function generator and transformer that produced an open-circuit 0.9 V peak-to-peak sine wave at 100 Hz, the following scope traces were recorded⁶:

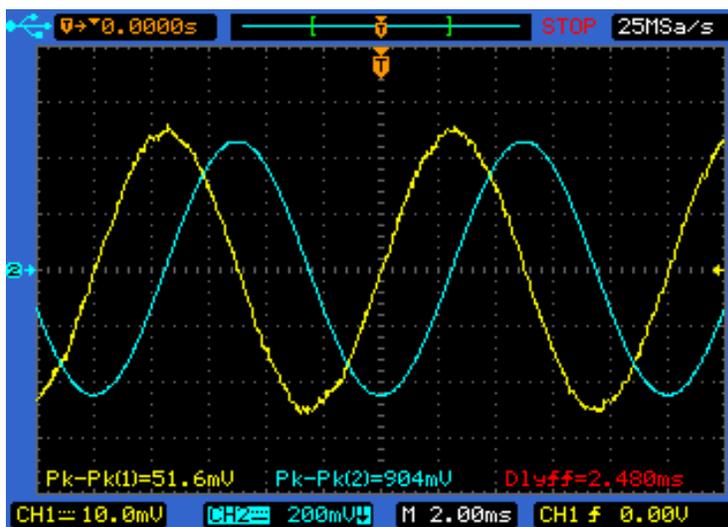


Figure 10: Scope trace of capacitor and resistor

The scope was set up to measure the peak-to-peak voltages and the delay between the two signals. Channel 1 (the yellow trace) is the voltage across the 1 k Ω resistor and indicates the current through the resistor is (51.6 mV)/(978 Ω) or 52.8 μ A peak-to-peak (note that it is a more noisy measurement than the voltage across the capacitor). Channel 2 is the inverted voltage across the capacitor showing 0.904 V peak-to-peak and a delay of 2.48 ms with respect to the current. Thus, for a

⁵ Nearly any small transformer should work. It is suggested that you use one that does not introduce much distortion of the sinusoid from the function generator.

⁶ These measurements were made with a B&K Precision 2542B-GEN oscilloscope, a convenient tool for such tasks because it contains a built-in function generator.

capacitor, we experimentally see that the current leads the voltage.

Since the sinusoid's period is 10 ms, the phase angle of the current with respect to the voltage is:

$$\delta = \left(\frac{2.48}{10}\right)360^\circ = 89.28^\circ$$

The voltage across the capacitor and the current through it are:

$$V_c = 0.904 \text{ V} \angle 0^\circ$$

$$i_c = 52.8 \text{ } \mu\text{A} \angle 89.28^\circ$$

We thus have the three needed numbers mentioned above from direct measurement. The capacitor's impedance is the ratio of the voltage across the capacitor to the current through the capacitor:

$$Z = \frac{0.904 \text{ V} \angle 0^\circ}{52.8 \text{ } \mu\text{A} \angle 89.28^\circ} = 17.1 \text{ k}\Omega \angle -89.28^\circ$$

The capacitor's measured impedance is **17.1 kΩ ∠ -89.3°**.

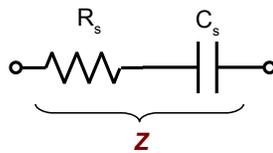
Two B&K Precision LCR meters were used to measure the impedance of this capacitor at 100 Hz. The results of the three measurements rounded to three significant figures are:

Method	Z , kΩ	Angle, °
B&K 886	17.3	-89.5
B&K 879B	17.6	-89.5
B&K 2542B-GEN (scope)	17.1	-89.3

The discrepancy between the two meters is a few tenths of a percent larger than would be suggested by their accuracy specifications. If you needed an accurate impedance measurement, more investigation might be warranted.

A conservative estimate of the uncertainty of the impedance measured using the scope is about 9% of the measured value for the magnitude and 0.25% for the phase⁷. Measurement equipment with lower uncertainties would result in lower impedance uncertainties.

Once the impedance of the device is known, other parameters can be calculated using the formulas given in the section, **Some formulas related to impedance**. As an example, we'll calculate the parameters of the series model for this capacitor:



$$Z = R_s + \frac{1}{j\omega C_s}$$

The oscilloscope-measured impedance was **17.1 kΩ ∠ -89.28°**. Converting to rectangular coordinates gives **215 - 17.1 × 10³ j**. The real part gives us $R_s = 215 \text{ } \Omega$. Since the frequency was 100 Hz, we can calculate:

$$C_s = \frac{1}{17.1 \times 10^3 \omega} = \frac{1}{17.1 \times 10^3 (2\pi (100))} = 93.1 \text{ nF}$$

The two LCR meters measured series capacitance values close to this number.

⁷ These numbers were calculated using linear uncertainty propagation, no correlation, and defining the uncertainty to be the half-width of the DC measurement accuracy given in the scope's specifications.

In summary:

- ◆ Impedance is most directly measured by virtue of its definition as a complex voltage to current ratio.
- ◆ If you have an oscilloscope and function generator, you can measure component and circuit impedances with them. At low frequencies such as that of the AC line or 1 kHz range, putting together a measurement setup on the bench works fine. However, if you want the impedance at higher frequencies, you will probably want to be careful with the physical layout to minimize the effects of parasitic impedances. A prudent experimenter would also perform an open/short calibration to be able to compensate for leads and fixtures (see the **Open/short calibration** section). Even though that section discusses such calibration for LCR meters, the identical process and analysis would be done when making oscilloscope measurements to compensate for measurement leads and fixtures.
- ◆ If you require impedance measurements with lower uncertainties, the method presented in this section can be utilized with a more sophisticated voltage measurement device and a frequency counter that can measure time intervals between the two sinusoids.
- ◆ For making numerous impedance measurements, an LCR meter is faster and more convenient than using a scope and function generator.

Bridge circuits

Historically-important methods of measuring impedance are based on the Wheatstone bridge. However, bridge circuits are not used much in modern LCR meters.

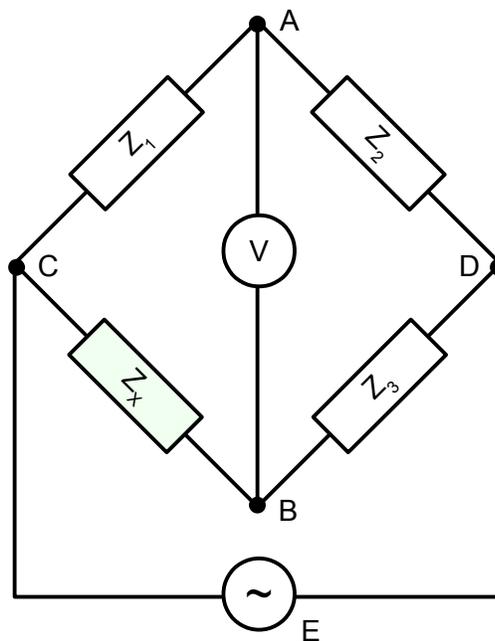


Figure 11: Wheatstone bridge

The measurement procedure is to set the sinusoidal voltage E to a suitable value and adjust the three impedances Z_1 , Z_2 , and Z_3 so that the voltages at points A and B are equal (i.e., V is 0). This is called nulling or balancing the bridge. In balance, the current through the arm CBD of the bridge is $E/(Z_x + Z_3)$ and the current through the arm CAD is $E/(Z_1 + Z_2)$. Since the voltages at A and B are equal with the bridge balanced, the voltage drop across Z_2 is the same as the voltage drop across Z_3 . Similarly, the voltage drops across Z_1 and Z_x are equal to each other.

$$\frac{E Z_2}{Z_1 + Z_2} = \frac{E Z_3}{Z_x + Z_3}$$

or

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

Note the balance is independent of the applied voltage E , although the sensitivity of the bridge will be proportional to E .

Remember that these four Z values are phasors, which means there are two components of each impedance that must be adjusted independently to achieve a balance in general. In practice, two or three of these impedances are usually adjustable resistances with low reactances to reduce the number of adjustments to null the bridge.

Some formulas related to impedance

Also refer to the formulas derived in the section **Impedance**. For both inductors and capacitors, we have $R_s R_p = X_s X_p = |Z|^2$ where X is a reactance.

You can estimate lead inductance using 1 nH per mm of lead length. A piece of RG-58/U coax has a capacitance of approximately 82 to 95 pF per meter of length and an inductance of about 0.25 μ H per meter of length.

In the following formulas, we use:

ϵ_0 = permittivity of free space = 8.854×10^{-12} F/m

μ_0 = permeability of free space = $4\pi \times 10^{-7}$ H/m = 1.257×10^{-6} H/m

κ_e = relative permittivity of the intervening material = 1.0006 for air

κ_m = relative permeability of the intervening material = 1.00000037 for air

C = capacitance in F

L = inductance in H

The capacitance of a parallel plate capacitor with n equally-spaced parallel plates is:

$$C = \frac{\epsilon_0 \kappa (n-1) A}{d} \quad (11)$$

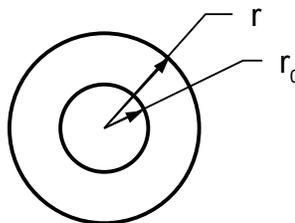
where

n = number of plates in capacitor

A = area of one plate in m^2

d = distance between two adjacent plates in m

For two concentric conductive cylinders:



$$C = \frac{2\pi\epsilon_0\kappa h}{\alpha} \quad L = \frac{\mu_0\kappa_m h\alpha}{2\pi} \quad \alpha = \ln \frac{r}{r_0} \quad h \gg r \quad (12)$$

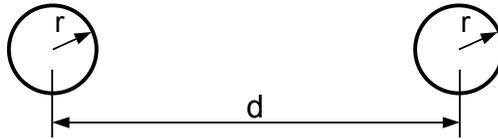
where

h = length of conductors in direction perpendicular to figure in m

r = radius of outer conductor in m

r_0 = radius of inner conductor in m

For a two-conductor transmission line:



$$C = \frac{\pi\epsilon_0\kappa_e h}{\ln \frac{d-r}{r}} \quad L = \frac{\mu_0\kappa_m h}{\pi} \ln \frac{d}{r} \quad \frac{d}{r} \gg 1 \text{ and } h \gg r \quad (13)$$

where

h = length of the conductors in m

d = distance between the centers of the conductors in m

r = radius of the conductors in m

Capacitance

Capacitive reactance is $(2\pi f C)^{-1}$ where f is frequency in Hz and C is the capacitance in F. If you memorize that $(2\pi)^{-1} = 0.159$, you'll be able to make capacitive reactance calculations easier by hand, especially for decade values of frequency.

For example, a 125 pF capacitor at 10^5 Hz has a reactance of:

$$\underbrace{0.159}_{\frac{1}{2\pi}} \left(\underbrace{\frac{1}{125 \times 10^{-12}}}_{\frac{1}{C}} \right) \underbrace{\frac{1}{10^5}}_{\frac{1}{f}} = 0.159 \left(\frac{10^9}{0.125} \right) 10^{-5} = 0.159(8) 10^4 = 12.72 \text{ k}\Omega$$

which also relied on knowing 1/8 is 0.125.

$$\begin{aligned}
\mathbf{Z} &= R_s + \frac{1}{j\omega C_s} = \frac{\frac{R_p}{j\omega C_p}}{R_p + \frac{1}{j\omega C_p}} = \frac{D^2 R_p + \frac{1}{j\omega C_p}}{1 + D^2} \\
D &= \frac{1}{Q} = \omega R_s C_s = \frac{1}{\omega R_p C_p} \\
R_s R_p C_s C_p &= \frac{1}{\omega^2} \\
C_p &= C_s \left(\frac{1}{1 + D^2} \right) \\
C_s &= C_p (1 + D^2) \\
R_p &= R_s \left(\frac{1 + D^2}{D^2} \right) = \frac{1}{\omega C_p D} \\
R_s &= R_p \left(\frac{D^2}{1 + D^2} \right) = \frac{D}{\omega C_s}
\end{aligned} \tag{14}$$

Inductance

Inductive reactance is $2\pi fL$ where f is frequency in Hz and L is the inductance in H. If you memorize that $2\pi = 6.28$, you'll be able to make inductive reactance calculations easier by hand, especially for decade values of frequency.

For example, a 125 μH coil at 10^5 Hz has a reactance of:

$$\underbrace{6.28}_{2\pi} \underbrace{(10^5)}_f \underbrace{125 \times 10^{-6}}_L = 6.28 (10^5) 0.125 \times 10^{-3} = \frac{62.8}{8} (10^1) = 78.5 \Omega$$

which also relied on knowing 0.125 is 1/8.

$$\begin{aligned}
\mathbf{Z} &= R_s + j\omega L_s = \frac{j\omega L_p R_p}{R_p + j\omega L_p} = \frac{R_p + jQ^2 \omega L_p}{1 + Q^2} \\
Q &= \frac{1}{D} = \frac{\omega L_s}{R_s} = \frac{R_p}{\omega L_p} \\
D &= \frac{1}{Q} = \frac{R_s}{\omega L_s} = \frac{\omega L_p}{R_p} \\
L_p &= L_s \left(\frac{1 + Q^2}{Q^2} \right) = L_s (1 + D^2) \\
\omega^2 &= \frac{R_s R_p}{L_s L_p} \\
R_s &= R_p \left(\frac{1}{1 + Q^2} \right) = D \omega L_s \\
R_p &= R_s (1 + Q^2) = Q \omega L_p
\end{aligned} \tag{15}$$

Using a reactance chart

The reactance chart shown in Figure 12 is convenient for use with LCR meters that make measurements under 1 MHz. The horizontal axis is frequency in Hz and the vertical axis is reactance in ohms. The colored diagonal lines indicate capacitance in blue and inductance in red.

To find a reactance: Given a frequency in Hz and an inductance or capacitance, locate the frequency on the horizontal axis and read vertically up to the intersection point with the blue or red line corresponding to the inductance or capacitance. Read the reactance horizontally from the intersection point to the left on the reactance axis. For example, a 100 nF capacitor has a reactance of 1.6 k Ω at 1 kHz.

To find an inductance or capacitance: Given a frequency in Hz and a reactance in ohms, locate the intersection point for the frequency and reactance. Then read off the closest blue line for capacitance or red line for inductance. For example, find the inductance that has a reactance of 10 Ω at 100 Hz. From the intersection point of 100 Hz and 10 Ω , the nearest red line is 20 mH. Interpolation gives the value of 16 mH.

To find an LC resonant frequency: Given a capacitance C and an inductance L, find where their interpolated blue and red lines, respectively, cross. Read down from the intersection point to find the resonant frequency, which is the frequency where their reactances are equal. For example, find the resonant frequency of a 100 nF capacitor and a 1 mH inductor. Read down the blue 100 nF line until it intersects the red 1 mH line. From the intersection point, read perpendicularly down to the frequency axis. In this case, the resonant frequency is 16 kHz.

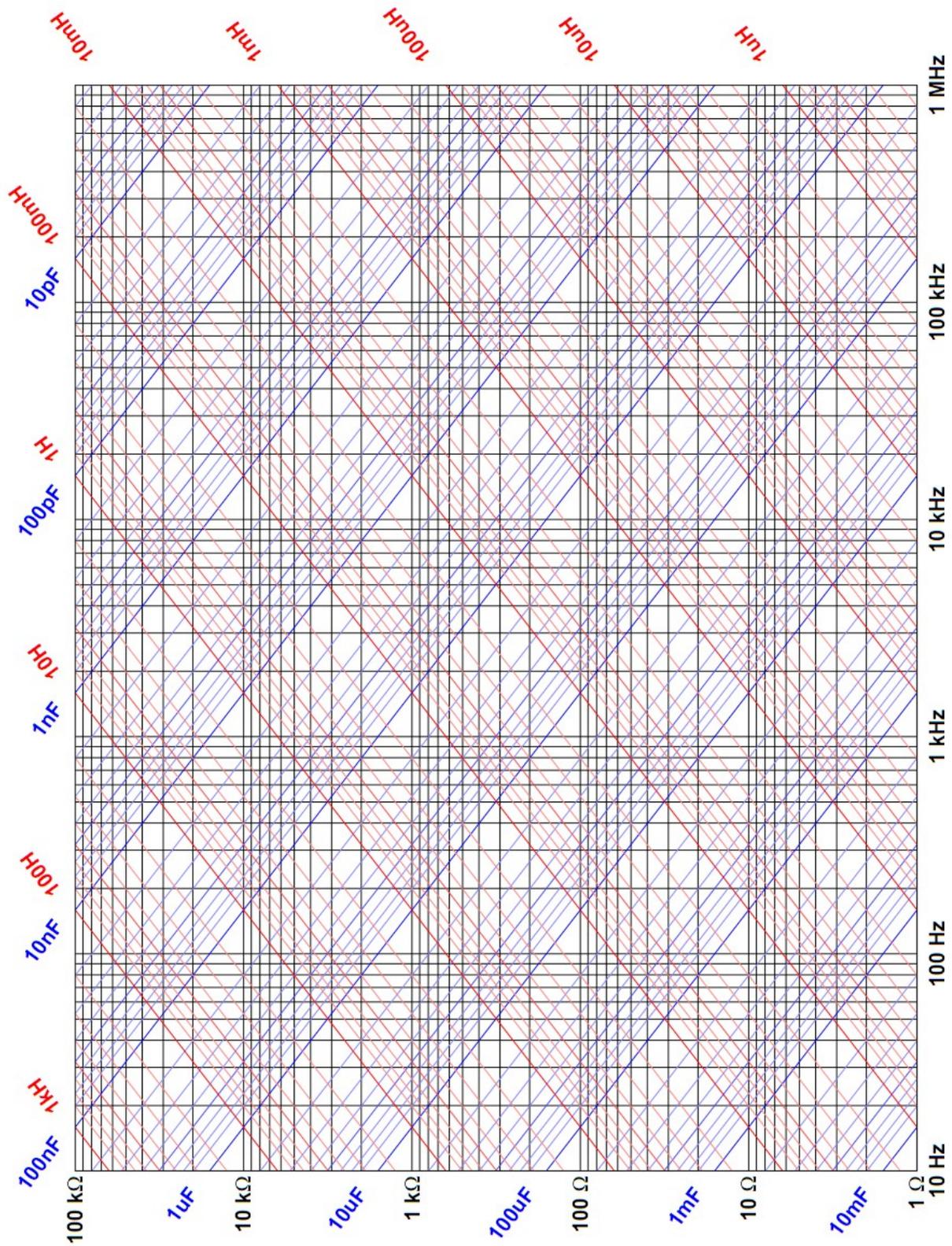
The resonant frequency of an LC circuit is the frequency f in Hz where the reactances are equal. This means:

$$2\pi fL = \frac{1}{2\pi fC}$$

or

$$f = \frac{1}{2\pi\sqrt{LC}}$$

The number 16 that appears in the examples above comes from the value of $(2\pi)^{-1} = 0.159$, which makes it a worthwhile constant to memorize when using frequencies and inductances/capacitances that are multiples of 10.



Reactance Chart for B&K LCR Meters

Figure 12: Reactance chart

LCR Meter Features

Meter types

There are a number of different types of LCR meters on the market.

Handheld battery-operated: These are typically small instruments about the same size as a digital multimeter. They have advantages of portability and are convenient to take to a remote site. They typically don't have the accuracy or measurement ranges of bench instruments.

Bench instruments: Bench instruments are larger than handheld meters, usually more expensive, and can include extra features such as the ability to measure voltage and current to make the instrument more useful at the bench. These meters also run off line power and can be left on for long periods of time without worrying about a battery going dead just before you need the instrument.

Lab-grade instruments: These are high-end instruments that measure over significant frequency ranges and component sizes. They are the most expensive instruments and sometimes are known under other names such as "network analyzer" or an "impedance analyzer".

Component meters: These meters measure fewer parameters than an LCR meter. For example, the B&K Precision 830C and 890C are dedicated capacitance meters. They work by applying a constant DC current to a capacitor and charges and discharges the capacitor. Contrast this to an LCR meter that measures a capacitance by measuring impedance with an AC signal at a chosen frequency. These more specialized meters may also have features that make certain tasks like sorting components easier to do. If your needs require knowing this DC-measured capacitance, you'll probably prefer the capacitance meter. If you want to know the dissipation factor or the capacitance at various frequencies, you will probably want to use an LCR meter for your measurements. Compare data sheets and manuals to help you decide what you need.

Selectable test frequencies

Because impedance is a function of frequency and application uses can benefit from knowing the impedance at the frequencies designed for use, it is useful to have an LCR meter that can make its measurements at different frequencies.

The two most popular frequencies for measurement are double the line frequency (i.e., 100 or 120 Hz) and 1 kHz. Twice the line frequency is used for filter capacitors and chokes that typically see a full-wave-rectified waveform to filter.

For many applications, being able to measure at twice the line frequency and 1 kHz provide enough flexibility. More sophisticated LCR meters include more measurement frequencies, such as 10 kHz, 100 kHz, and higher. Higher-end LCR meters can sweep the frequency and plot impedance magnitude and phase as a function of frequency.



Figure 13: Frequency sweep function on B&K Precision 891 LCR meter

Selectable test amplitudes

While it is well-known that impedance depends on frequency, it may be surprising to some that impedance can also depend on the amplitude with which it is measured. In reality, this isn't surprising behavior when one considers the voltage-current relationships of various components. For example, the resistance of a diode depends on the measurement voltage. This non-linear dependence of current on voltage is true of many components, especially for AC conditions. In fact, it could be argued that all components have such nonlinear V-I relationships (just keep doubling the voltage until you're convinced the relationship is nonlinear).

Relative mode

The relative measurement mode allows a standard part to be measured and then have subsequently-measured parts displayed relative to the standard's value. This makes it easier to compare measured values.

As an example of the use of relative mode, a B&K Precision 879B LCR meter was set to measure parallel capacitance at 1 kHz. The meter's open/short calibration was used to zero out the effects of the measurement leads.

A 100 nF nominal capacitor (actual value was 90.05 nF) was used as a standard. This standard capacitor was connected to the meter and the REL button was pressed. Then five capacitors from the same lot were measured relative to this standard capacitor; the results were (sorted by value):

Capacitor	ΔC , nF	% deviation
1	0.18	0.2
3	2.54	2.8
5	2.55	2.8
2	6.87	7.6
4	7.81	8.7

Note all five capacitors were larger than the standard (you'd expect about half to be less than and about half to be greater than the standard). The % deviation column shows the calculated deviation from the reference capacitor's value. These numbers can be compared to the % deviation measured in the following section.

Tolerance mode

Some LCR meters provide the ability to sort components within specified tolerance bounds. For example, the B&K Precision 879B LCR meter allows you to sort components within $\pm 1\%$, $\pm 5\%$, $\pm 10\%$, or $\pm 20\%$ of a nominal value. We'll use the same five capacitors and standard capacitor used in the previous section to illustrate tolerance mode.

The meter was set to tolerance mode after performing an open/short calibration. The standard capacitor was connected to the leads and a stable parallel capacitance was measured. The TOL button was then pressed to enter tolerance mode. The meter's display shows the % deviation from the standard capacitor and the measured capacitance value. The five capacitors in the previous section measured % deviations as follows (the capacitor's number doesn't necessarily agree with the numbers used in the previous measurements, as they were randomly selected from a pile). The measurements were sorted by deviation:

Capacitor	% deviation
3	0.9
5	2.0
2	2.3
1	7.2
4	8.3

Comparing the % deviation in this table to the calculated % deviation in the previous table gives you a feel for the repeatability of the measurement (within about half a percent).

Suppose we wanted to select a group of such capacitors that were within 5% of the standard value. Pressing the TOL button twice shows 5% in the display. When a capacitor is measured, the meter will give a single audible beep if the measured value is within tolerance and three beeps if it is out of tolerance. This allows a user to quickly select a set of components.

4-wire measurements

Some LCR meters use a 4-wire connection to the device under test. As explained in the section, **2-, 3-, and 4-wire measurements**, this is a measurement method that uses separate jacks/connectors for the current measurement and the voltage measurement. The benefit is that the lead resistance is not part of the measurement, allowing low-value impedances to be measured. Most bench LCR meters use a 4-wire connection measurement to the device under test.

For example, the B&K Precision 885 can use a 4-wire measurement to measure DC resistances down to 1 m Ω . Contrast this to the typical digital multimeter that uses leads that add around 0.2 Ω to a low-resistance measurement. These 4-wire LCR meters are especially convenient when used with Kelvin clips that allow easy connection to the device under test.



Figure 14: 885 LCR meter with Kelvin clips

ESR measurements

The ESR is the real part of the impedance when the series model is used. As the capacitor is probably the lowest impedance device in the circuits electrically connected to the capacitor, the LCR meter should be able to distinguish capacitors with unusually high ESR. Such measurements are typically made at 10 kHz or 100 kHz for best sensitivity.

Connectivity

Some LCR meters allow connection to a computer via USB, GPIB, and serial interfaces. An advantage of such a computer connection is that special measurement situations can be accommodated. For example, B&K Precision provides software with their 878B and 879B LCR meters, which allows the instrument to be configured remotely. The software also gives users the ability to log measurements on the computer and export the data to an Excel or text file.

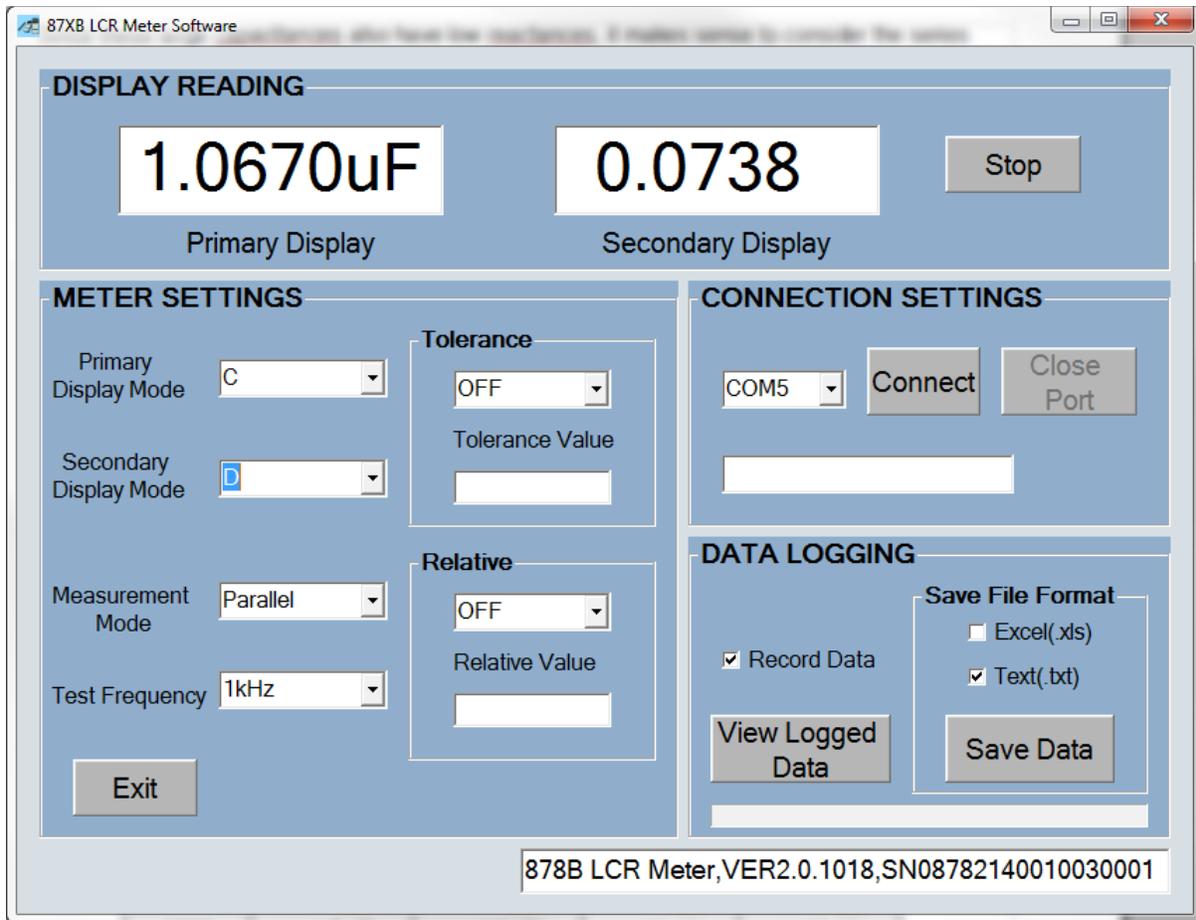


Figure 15: B&K Precision 878B/879B LCR meter software

Voltage and current measurements

Some LCR meters provide voltage and current measurements in addition to LCR and impedance measurements. Such features can be useful to allow the instrument to be used as a general troubleshooting instrument.



Figure 16: B&K Precision 889B bench LCR meter with voltage/current measurement capabilities

Lead slots and surface mount tweezers

Many LCR meters have lead slots. These are terminal connections that allow easy insertion of components with leads. If you have a bench LCR meter, it may have an optional attachment that provides the same features. Here are lead slots for the B&K Precision 879B LCR meter:



Figure 17: Lead slots measurement

You'll find you use these lead slots a lot if you use components with leads. If you use a lot of surface mount devices, make sure to get surface mount tweezers as it will also make measurements easier.

Making LCR Measurements

Safety

The basic safety rule for using an LCR meter is to never make measurements on any circuit that has a voltage present or is connected to a source of power. This includes attempting to make measurements on capacitors that are not discharged, which is often the cause of LCR meter damage. Before making measurements with an LCR meter, ensure all capacitors are completely discharged by connecting a suitable resistance across the capacitor's terminals. For extra caution, use a digital multimeter to verify the voltage across each capacitor is zero. Some capacitors can exhibit dielectric absorption and may take extra time to completely discharge.

It is also worth extra effort to ensure that all power is off in line-powered circuits. Connecting an LCR meter across the full line voltage may destroy the instrument and making measurements in a circuit with line voltages can be hazardous.

If you are measuring components that are sensitive to voltages, ensure the test voltage your LCR meter applies to the device under test is safe for the device under test.

Test frequency

A common question is what frequency should be used to measure a component or circuit. The short answer is to use the frequency at or near where the component or circuit will be used.

Large electrolytic capacitors are often used as power supply filters, so they should be tested at twice the line frequency. This is the frequency seen from full-wave rectified sine waves. Smaller capacitors are more likely to be used at higher frequencies, so they should be tested at those frequencies. Large inductors are often used as chokes and can be tested at line frequencies. Smaller inductances less than 1 mH are often used at higher frequencies and should be tested at the frequencies they will be used at.

In general, an LCR meter measurement at one frequency does not allow you to predict behavior at another frequency, especially as the frequency goes up. If your LCR meter can only measure at frequencies up to 10 or 100 kHz and you need to know the impedance at 1 MHz or above, you can extrapolate using the measured value and the equation for the reactance, but your extrapolation will probably be in error because of the effects of parasitic reactances. Viable options in this case are to find an LCR meter with a wider frequency range or measure the impedance with a function generator and oscilloscope.

Open/short calibration

There are two types of calibration in the context of LCR meters:

- ◆ Instrument calibration to allow traceability to national standards (see the section **Range and accuracy of LCR meters** for more details).
- ◆ Open and short calibration (also called compensation) to correct for lead/fixtures parasitic impedances.

For the best realizable accuracy in your LCR meter's measurements, you should perform an open/short calibration when changing the excitation signal level, frequency, or parameter being measured.

A schematic model of an LCR meter making a measurement is:



Figure 18: LCR meter measurement model

where the dashed leads are regarded as electrically ideal and do not contribute anything to the measurement.

The simplest measurement situation is where a component with leads is inserted into the LCR meter's terminals and the measurement is made. Especially at the frequencies used by handheld LCR meters, the parasitic impedances due to the leads are essentially ignorable. However, this may not be true for other components or circuits. For example, a surface mount component might need SMT tweezers to provide a measurement. The tweezers represent the leads and fixture, so their impedance needs to be removed from the measurement. This removal of the effect of the lead's impedance is the purpose of the open/short calibration.

An open calibration is where the LCR meter is told the DUT is an open circuit. The meter then performs an impedance measurement and stores the result.

A short calibration is where a low resistance connection is made between the test leads' or fixture's terminals and the meter is told the DUT is a short. It performs an impedance measurement and stores the result.

These two calibration measurements are then used by the meter to compensate for the impedances introduced by the leads and fixture.

Because this is an important concept, let's look at it in more detail. Figure 18 can be replaced by the following equivalent circuit model:

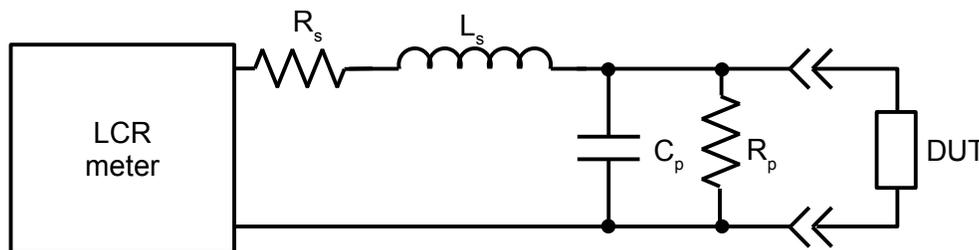


Figure 19: Model of fixture/lead parasitic impedances

The LCR meter is modeled as a two-lead measuring device. An LCR meter that used 4-wire measurements would not be conceptually different, except for some more terms in the model. The leads are modeled as having a resistance R_s and an inductance L_s . As the leads are likely wires insulated with dielectric insulating material, these leads also form a lossy capacitor that is modeled by the capacitance C_p and resistance R_p .

The user makes sure the DUT is not connected to the leads/fixture and the meter is told to calibrate itself to an open circuit. This is represented by the measurement of the two impedances in series:

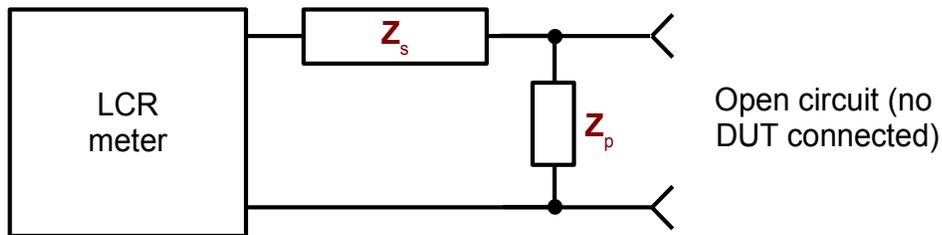


Figure 20: Open-circuit impedance measurement

The meter measures the impedance seen on its input ports and stores the value. This impedance is

$$Z_0 = Z_s + Z_p$$

Then the user connects a short to the test terminals. This shorts out Z_p and the meter measures Z_s . The meter can then calculate Z_p from $Z_p = Z_0 - Z_s$. Now Z_p and Z_s are known. Finally, the user measures Z_m , the impedance of the DUT combined with the lead/fixture impedance:

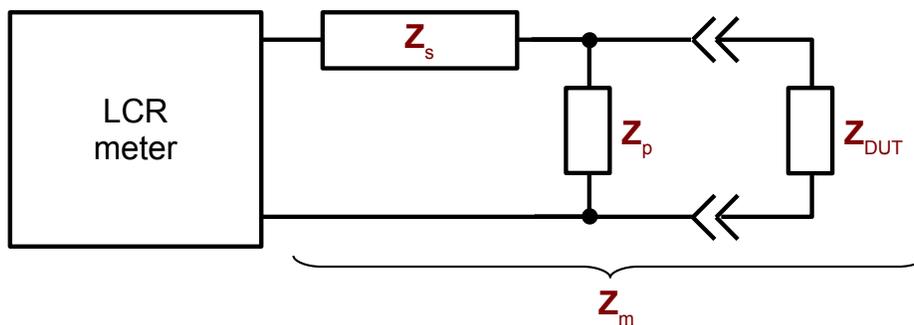


Figure 21: Total impedance measurement

$$Z_m = \left[\frac{1}{Z_{DUT}} + \frac{1}{Z_p} \right]^{-1} + Z_s$$

The impedance of the DUT is then calculated from:

$$Z_{DUT} = \frac{Z_m - Z_s}{1 - (Z_m - Z_s) Y_p}$$

where

Z_m = measured value of DUT, leads, and fixture

$Z_s = R_s + j\omega L_s$

$Y_p = \frac{1}{R_p} + j\omega C_p$

There are situations with complicated leads and fixtures where this open/short calibration method is not sufficient to remove the parasitic impedances associated with the leads and fixtures. Such situations are beyond the scope of this document.

It might occur to you that it could be easier to just press the REL button on your LCR meter to subtract out the contribution of the leads and the fixture. This is tempting because it is quicker than an open/short calibration. However, note that the impedance being subtracted is $Z_s + Z_p$. $|Z_p|$ is probably much larger than $|Z_s|$ and this may not result in as good a measurement as where Z_s and Z_p are determined separately. In fact, it makes an instructive experiment that you can perform with a selection of components and see how well using the relative measurement works. You may find that it doesn't work for low impedance measurements as well as an open/short calibration.

There are also situations where you can ignore the impedances of the leads and fixture. For example, a 1 m RG-58/U coaxial cable, dual banana to BNC adapter, and a 150 mm alligator clip breakout have a capacitance when connected of about 0.1 nF. This is ignorable for measurements of capacitance above 100 nF.

2-, 3-, and 4-wire measurements

There are various methods of connecting an LCR meter to the device or circuit being tested. We'll look at three of them.

2-wire measurements

A 2-wire connection between an LCR meter and a DUT is:

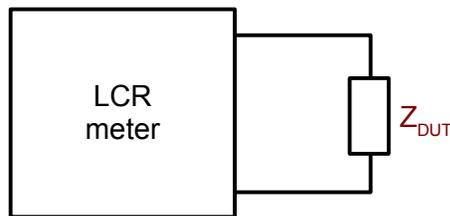


Figure 22: 2-wire impedance measurement

This is the easiest way to connect a DUT to an LCR meter. However, it suffers from the drawback that the impedance of the leads and devices to connect to the DUT are included in the measurement. An equivalent circuit of the real measurement situation could be:

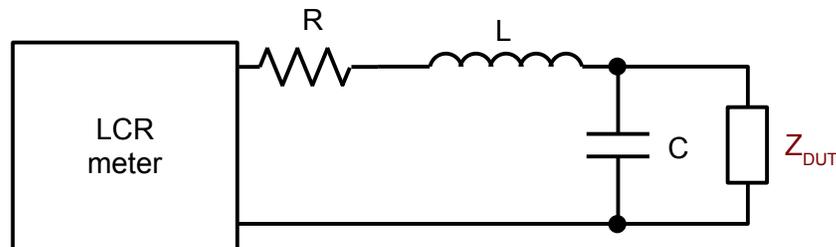


Figure 23: 2-wire impedance measurement model

The resistance of the leads is modeled by R and the lead inductance is modeled by L . Because the leads may be relatively close in space and separated by a dielectric, this forms a capacitor C . These impedances are called **parasitic** because, like a parasite, they are unwanted and can be hard to get rid of.

By performing an open/short calibration, you may be able to remove much or most of this parasitic impedance -- it depends on your needs and what you're measuring.

There are situations where the measurement is negligibly influenced by the lead/fixture impedance. For example, measuring the capacitance of a 1 mF capacitor can be done with a 1 m coaxial cable and an alligator clip breakout, which adds less than 100 pF capacitance to the measurement. The lead/fixture impedance only contributes 0.00001% to the measured value, which is far smaller than the measurement uncertainty.

However, if you were measuring a 100 pF capacitor, the lead/fixture stray capacitance could be significant and would introduce a large systematic error if you didn't compensate for it.

Here's a measurement example:

A nominal 125 pF capacitor with leads was measured. A B&K Precision 879B was used to measure the parallel capacitance C_p . The results under different measurement conditions at 10 kHz were as follows. The coaxial connection was a 0.6 m coaxial cable with a dual banana plug adapter and a 150 mm alligator plug breakout. The connection's capacitance was 69.33 pF as measured by the meter.

Connection	Correction	Measured value, pF
Into lead slots	None	126.64
	REL to remove open circuit C	126.61
	Open/Short calibration	126.61
Coaxial	None	196.47
	REL to subtract lead C	127.97
	Open/Short calibration	126.85

Table 2: Lead slots vs coaxial measurements

Correcting the uncorrected coaxial measurement gives 196.47 - 69.33 or 127.14 pF.

The same capacitor was measured with the B&K Precision 886 LCR meter, using both the lead slots and the optional 4-wire cable with Kelvin clips.

Connection	Correction	Measured value, pF
Into lead slots	None	126.4
	REL to remove open circuit C	126.5
	Open/Short calibration	126.5
4-wire cable	None	127.9
	REL to subtract lead C	126.6
	Open/Short calibration	126.8

Table 3: Lead slots vs 4-wire cable measurements

In all cases, it was felt the most stable measurement was obtained when the open/short calibration was used to correct for the leads and fixturing. This open/short calibration also allowed the measurements with and without leads to agree within a few tenths of a percent. Taking the mean of the two Open/Short calibration measurements for each meter shows they agree on the capacitor's value within about a tenth of a percent. This is better agreement than the meters' accuracy specifications would indicate (0.5% accuracy for these measurements).

3-wire measurements and guarding

A guarded measurement using an LCR meter can produce more stable results than an unguarded measurement. The connection method uses shielded cable to connect to the DUT and the cables' shields are connected to the guard terminal:

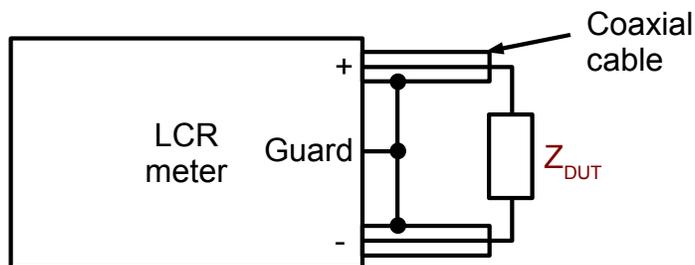


Figure 24: 3-wire impedance measurement

This type of connection can help remove some parasitic capacitance and improve the ability of the LCR meter to measure high impedances such as resistances on the order of 10 MΩ or above.

4-wire measurements

The 4-wire measurement is well-known in the context of measuring resistance and is often referred to as a Kelvin measurement. The same connection topology can be used for making LCR meter measurements, although your LCR meter needs to support such connections. The schematic diagram is:

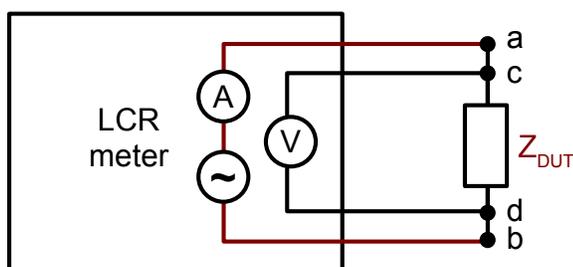


Figure 25: 4-wire impedance measurement

The current circuit (shown in red) applies an AC current to the DUT and the ammeter measures the current. The voltmeter measures the voltage drop across the DUT. A key feature of a 4-wire connection is that the voltmeter connections “c-d” to the DUT are inside the ammeter connections “a-b”. This means that any contact resistance at a or b that could cause a voltage drop (and thus be measured by a 2-wire measurement) is ignored by the 4-wire measurement procedure.

The 4-wire measurement is useful for low impedance and low DC resistance measurements, as the effects of the leads are eliminated. If you are performing AC resistance measurements, make sure you use open/short calibration to compensate for the parasitic impedances in the leads for best measurement accuracy.

4-wire measurements can also be done with shielded cables where the shield is connected to a guard terminal (this is sometimes called a 5-wire measurement). This can reduce noise and measurement uncertainty.

Range and accuracy of LCR meters

It's important to ensure that you don't measure components outside of the specified ranges of values specified in the LCR manual. The LCR meter's measurement uncertainty typically grows as you approach the meter's largest or smallest range.

Measurement uncertainty

Measurement uncertainty of LCR meters is usually given in the user manual under the specifications for accuracy. A common method of specifying accuracy is to show it in the form of $\pm(X\% + Y)$ where X is a percentage of the measured value and Y is an integer specifying a count of the least significant digit in the measurement. The meter's different ranges will typically have different accuracy specifications. The meter's accuracy specifications also do not take into account the effects of leads and fixturing.

The following is an example of the calculation of the accuracy for a measurement made with the B&K Precision 886 LCR meter.

The component measured was a choke whose parallel inductance measured $L_p = 2.611$ H at 1 kHz with $Q = 7.996$. The manual for the 886 states that the measurement accuracy for the instrument is "0.2% \pm 1" for inductance in the 1.591 mH to 15.91 H range. This means the stated accuracy is 0.2% of the measured value plus 1 digit in the least significant digit position, or 1 mH. Thus, the final accuracy statement is $(2.611 \pm (0.0052 + 0.001))$ H or 2.611 ± 0.0062 H. For this measurement, the accuracy is thus 0.24% of the measured value.

Unless otherwise stated, the interpretation of the accuracy is that it gives an interval within which the measured value would lie if it could be compared to a national standard value by a significantly better measurement process.

If you wish to translate this accuracy into a measurement uncertainty, you'll have to make an assumption about how many standard deviations of the measured value comprises the half-width of the accuracy interval. This is rarely specified. However, manufacturers know the distribution of their instruments' measurement capabilities and these accuracy statements are made to reflect all measurements made with all instruments produced by the manufacturer's production line. A conservative assumption is to make the uncertainty equal to the accuracy half-width.

In general, you'll find the LCR meter's measurement uncertainty as a percentage of reading grows as the measured value approaches the high and low measurement limits of the meter. For example, low capacitance levels on the order of 1 pF and lower can present high impedances that result in low currents. High-value inductors can have similar high impedances. These current levels can be influenced by environmental noise and thus contribute to measurement uncertainty.

Measurement standards

To be able to trust the readings from your LCR meter, it is advisable to have various standards that are stable over time.

Purchased commercial standards: If you require traceability to a national standards organization, then purchasing commercial standards and having your instrument calibrated on a regular basis is a good approach. Because such standards and calibration services can be expensive, it may make economic sense only if you can spread these costs over numerous LCR meters in the organization or if the cost of a mistake exceeds the standards and calibration costs.

Standards constructed in-house: You can construct your own standards. A parallel-plate capacitor can be constructed with a suitable dielectric material between the plates. If the permittivity of the dielectric is ϵ , the separation of the plates, t , is in m, and the area of the plates is A in m^2 , the capacitance is $\epsilon A/t$ in F. A rigid design with stable materials should result in a robust and stable standard. Such parallel plate capacitors will likely have capacitances on the order of a few hundred pF. If constructing coils with a desired inductance, using a ferromagnetic core can increase the inductance. Such coils can be in the 10 μ H to 1 mH range.

You may also be able to use existing items as standards. For example, a transformer with one primary and one secondary can provide two standard inductance values once they are calibrated and mounted in a container with suitable connectors.

Commercial components calibrated by a measurement lab: Since purchased commercial components can be low-cost, a practical source of standards is to select a set of commercial components, have their values calibrated, then treat them as reference standards. You'll want to check their calibrated values on a periodic basis to ensure that the values do not change over time. They can then be used with your LCR meters to generate working standards.

Since measurement standards can represent significant investments in time and effort, you'll want to establish procedures for using, storing, and calibrating these standards to ensure they remain stable and undamaged over time.

Measurement discrepancies

LCR meter measurements are more involved than digital multimeter measurements and at some point, you'll probably encounter measurement discrepancies. These can be confusing and frustrating, especially if you can't discover the cause of the discrepancy. In this section, we'll look at some of the things that can cause measurement discrepancies.

Many LCR meters start with a measurement of impedance⁸. As discussed elsewhere in this document (refer to the experiment **Measurement of impedance with an oscilloscope**), the impedance is calculated by dividing the voltage measured across the DUT by the measured current through the DUT -- and remember these are AC measurements made at a particular frequency.

Frequency: Since reactance is a function of frequency, one of the first things to do is **make sure you are measuring at the same frequency**. A factor of 10 error in the frequency leads to a factor of 10 error in the measured reactance. The effect on the impedance depends on the size of the real part. If we suppose that the reactance X is transformed into the reactance αX by a mistake in test frequency, then the magnitude of the impedance will be transformed to $\sqrt{R^2 + \alpha^2 X^2}$ and the tangent of the phase angle of the impedance will become $\alpha X/R$.

As a numerical example, assume R and X are both 1Ω . Then the magnitude of the impedance is $\sqrt{2} \Omega$ and the phase angle is 45° . If the reactance is reduced by a factor of $\alpha = 0.1$, then the magnitude of the impedance becomes 1.005Ω and the phase angle is 5.7° . If the reactance is increased by a factor of $\alpha = 10$, then the magnitude of the impedance is 10.05Ω and the phase angle is 84.3° .

Here's a to-scale plot of these impedance phasors to give you a feel for how big the effect of a 10X frequency mistake is:

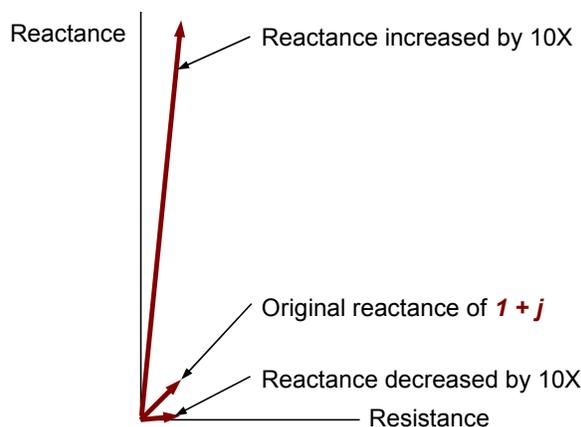


Figure 26: Effect of reactance frequency discrepancies

You can see the change in measured impedance can be large, so a large measurement discrepancy should make you suspect measurements at different frequencies.

⁸ There are actually a variety of impedance measurement methods for different frequency regimes.

Signal amplitude: The measured impedance can depend on the signal amplitude used as can the measurement uncertainty. Thus, if your LCR meter allows control over the measuring signal's amplitude, ensure you use the same amplitude for the two measurements.

Out of range: You may get strange or non-repeatable results if you measure a component outside the specified range of your LCR meter.

Equivalent circuit: For components with dissipation factors that are not close to zero, the series and parallel inductance or capacitance can differ significantly. Make sure you're comparing numbers for the same equivalent circuit. Unfortunately, it is often unclear which measurement model was used for a particular measurement if undocumented, making it difficult to duplicate the original measurement conditions.

Connection type: You may have made measurements on the same device or circuit with two different LCR meters and have been surprised by discrepancies in the measured values. One cause of this can be that you didn't make the same connection type to the DUT, which can be especially troublesome for low impedance measurements. Such low impedance measurement problems can be reduced by using an LCR meter that uses 4-wire measurements. Always remember that the leads and fixturing contribute to the measured impedance and using an open/short calibration can help compensate for this. However, since open/short calibrations take a little time, busy people sometimes neglect them. A discrepancy thus might be caused by the impedance of the leads or fixture.

DC bias: Another type of discrepancy can be a measured inductance that is different than what the inductor's manufacturer specifies. One cause of such discrepancies is that the manufacturer specified it for operation at a certain DC current bias, but you tested it at a different bias current or no bias current. Capacitors can also have their capacitance depend on the DC bias.

Parasitic impedances: A discrepancy can be caused by neglecting the parasitic impedances in the measurement leads/fixture, especially when the parasitic impedances are on the order of the actual impedance values you're trying to measure. Thus, for low capacitances and inductances, it's important to ensure that you've corrected for the parasitic impedances. The recommended way to do this is to perform an open/short compensation at the test conditions to be used.

Changes over time: Components have been known to change their values over time. Electrolytic capacitors are a good example, although it may slowly happen over time or stress. High-K ceramic capacitors can decrease their capacitance over time. Changing humidity levels may also influence component or circuit impedances. For instance, consider a hygroscopic ionic contaminant on a PC board that changes the leakage current between traces as a function of humidity.

History: Components and circuits can have complicated behaviors that depend on past history. For example, consider dielectric absorption or magnetic hysteresis in a ferromagnetic core. Unless you can ensure the part is tested in the same state as it was in for the previous measurement, you may see a discrepancy.

Some other examples are:

- An external magnetic field larger than the coercivity of an inductor's core could magnetize the core so that it operated at a different point on the hysteresis curve than the designer intended, even if the proper DC bias current was applied.
- A component's value could be permanently changed by an electrostatic discharge event.
- Exposure to the ultraviolet photons in sunlight could cause slow degradation of a plastic, leading to an electrical behavior difference.
- Excessive vibration could cause mechanical changes in a component or circuit.
- Environmental stresses can cause things to change their electrical behavior over time.

Temperature: Devices as well as the LCR meter itself can change their electrical characteristics as a function of temperature. A discrepancy can be caused by measurements at different temperatures. Dissimilar metals can cause thermoelectric biases. Temperature changes can cause permittivity or permeability changes.

Measure the same thing: When analyzing a discrepancy, make sure the two measurements actually measured the same thing. If your measurement used the parallel equivalent circuit model, but the other measurement used a more complicated equivalent circuit, it won't be surprising if you report different numbers -- and you may never be able to resolve the discrepancy.

Noise: As in all electrical measurements, noise can be a contributing factor to measurement uncertainty. Since an LCR meter makes current and voltage measurements, it can be influenced by noise. An example would be if you're operating the LCR meter next to a significant source of electromagnetic interference such as a large transformer or motor. The EMI could cause measurement discrepancies that could be hard to track down. Higher frequency noise from computers or switching power supplies could also be noise contributors. Noise can come from other sources too. Triboelectric noise or microphonics can occur when the test environment includes vibration and circuit components that can move relative to each other.

Calibration: If the LCR meter is out of calibration or has been handled roughly, it might not perform to its specifications. The fix is to make sure the instrument has been checked and calibrated by a suitable calibration lab. A good tactical tool for finding calibration problems is to keep a number of working standards on hand for checking the instrument.

Different instruments: A discrepancy can be caused by using two significantly different instruments. They may make measurements in different physical ways that are not directly comparable. While this would be unusual for an LCR meter because electrical standards are well-defined, it could be a corner case to consider when other things haven't explained the discrepancy.

Good practices

This section contains tips and suggestions to help you get the most out of your LCR meter.

Standards	Use measurement standards to help assure yourself the LCR meter is measuring what you think it is.
Record test conditions	To be able to repeat measurements in the future, use good lab practices in documenting the measurement conditions. Besides the measurement equivalent circuit model, instrument settings, calibration information, etc., record such things as instrument model number, serial number, time of day, temperature, humidity, location, and other things that might influence the collection or interpretation of measurements.

<p>Compensate leads and test fixture</p>	<p>After setting up all your LCR meter parameters, perform an open/short calibration. This helps ensure you get the best accuracy from the instrument. Manufacturers usually state that the instrument will perform to its specified accuracy only if a proper open/short calibration has been done.</p>
<p>Understand required measurement conditions</p>	<p>When measuring components or circuits, make sure you understand the measurement conditions the manufacturer or designer specifies. Failing to use the required conditions can result in measurement discrepancies. For example, if an inductor requires a DC bias for measurement, you need to ensure your measurement includes the proper bias current.</p>
<p>Environment</p>	<p>Be sensitive to how the measurement environment can differ from "standard". For example, making measurements in a cold warehouse can produce different readings than what you make at your bench.</p>
<p>Calibrated and properly functioning</p>	<p>Ensure the LCR meter is in calibration and functioning correctly. Double check the calibration with your working standards.</p>
<p>Avoid charged capacitors</p>	<p>Measuring a charged capacitor is the same as applying a DC bias to the LCR meter's input terminals. You may damage the instrument by doing this, especially with a capacitor that has a relatively high voltage on it.</p>
<p>Appropriate measurement model</p>	<p>Use the series model for reactances less than about 100 Ω and the parallel model for reactances larger than 100 Ω.</p>

<p>Don't confuse AC and DC resistance</p>	<p>LCR meters typically measure AC resistance and some will also measure DC resistance. Because of parasitic impedances, the DC and AC resistance values may be different.</p>
<p>Respect limits</p>	<p>Don't measure components with values outside the measurement limits of the meter.</p>
<p>Use the proper test frequency</p>	<p>Try to test the component circuit at the frequency at which it will be used.</p>
<p>Use your physical intuition</p>	<p>When possible, measure impedance in polar coordinates. The magnitude is in ohms and you can compare the measured value with your experiences. Remember that current is inhibited by either a resistance or reactance, so the impedance magnitude is important. The phase angle of the impedance tells you whether you're dealing with a capacitive or inductive reactance. The closer the absolute value of the phase is to 90°, the more pure the reactance and its power dissipation will be lower (i.e., low D and high Q).</p>

FAQ

What is admittance?

Admittance Y is defined to be the reciprocal of impedance:

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

Admittances are useful in analyzing parallel circuits because parallel admittances add algebraically to give the composite admittance. The real part of the admittance is called **conductance** G and the imaginary part is called the **susceptance** B . Both conductance and susceptance have physical units of siemens S^9 . The definition is sometimes given as:

$$Y = G + jB$$

Here is a quick demonstration of the utility of conductance. Suppose you have two resistors of 3Ω and 8Ω . What is their resistance when they are in parallel? The resistances can be converted to conductances of $0.333 S$ and $0.125 S$, and then added to get $0.458 S$.

The reciprocal of this is 2.18Ω . A calculation with the usual parallel resistance formula yields $(3)(8)/(3 + 8) = 24/11 = 2.18$, as we'd expect. The utility of admittance comes when performing calculations with phasors, as the equivalent impedance of a portion of a circuit with impedances in parallel can be calculated by adding the phasors representing the admittances. The result can then be converted back to an impedance by taking the reciprocal.

In truth, if you have a calculator that can handle complex numbers, you probably won't need to deal with admittances much when you do impedance calculations.

Why do I get a negative reading?

You may occasionally be surprised when you see an LCR meter measure a negative quantity. Some possible causes of this can be:

Wrong component model: You could be measuring the inductance of a capacitor or the capacitance of an inductor. This may be easy to demonstrate by setting the LCR meter to capacitance and shorting the leads. Set the LCR meter to measure inductance and leave the leads unconnected.

Relative mode: You have the LCR meter in relative mode and you're seeing a measured value below the value used as a reference. This should be resolvable by looking to see if the "REL" relative mode indicator is on in the display.

LC circuit: You could be measuring a circuit that contains both capacitance and inductance. A series LC circuit behaves like a capacitor at low frequencies and an inductor at high frequencies. A parallel LC circuit behaves like an inductor at low frequencies and a capacitor at high frequencies.

A motor measurement example

In this example, we measure the inductance, capacitance, and impedance of a motor winding as a function of frequency. Here is a table of measurements made with a B&K Precision 886 LCR meter for the high-speed winding of a 1/3 hp, 3-speed furnace fan induction motor as a function of frequency:

⁹ S stands for the SI unit of siemens and is 1 ampere per volt. The word siemens is both singular and plural in English usage, so it's proper to say "one siemens".

Frequency, kHz	L_s , mH	Q	C_p , nF	D	$ Z $, Ω	θ , deg.
0.1	18.23	1.869	-108000	0.534	12.99	61.85
1	16.17	5.890	-1562	0.169	103	80.36
10	13.66	4.398	-17.62	0.227	880.5	77.19
100	-2.236	2.999	1.02	0.333	1481	-71.56

Note the negative inductance and capacitances. Since the impedance is behaving like an inductor at low frequencies and a capacitor at high frequencies, here's an equivalent circuit model that might explain this behavior:

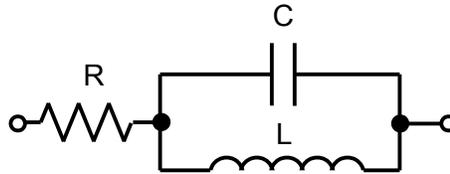


Figure 27: Fan motor stator equivalent circuit

The capacitance would arise physically because of the distributed capacitance between the wires of adjacent windings. Let's see if this lumped parameter model might adequately model this situation.

We can estimate R from the 100 Hz impedance measurement as $13 \cos(61.85^\circ)$ or 6.1 ohms (the DC resistance measured about 3 ohms, so this 6 ohms is a 100 Hz equivalent series resistance). If we assume the inductance L is 18 mH from the 100 Hz measurement and the capacitance is 1 nF from the 100 kHz measurement, we can plot how well this model predicts the measured impedances. The red dots are the measured values and the blue lines are the model's predictions.

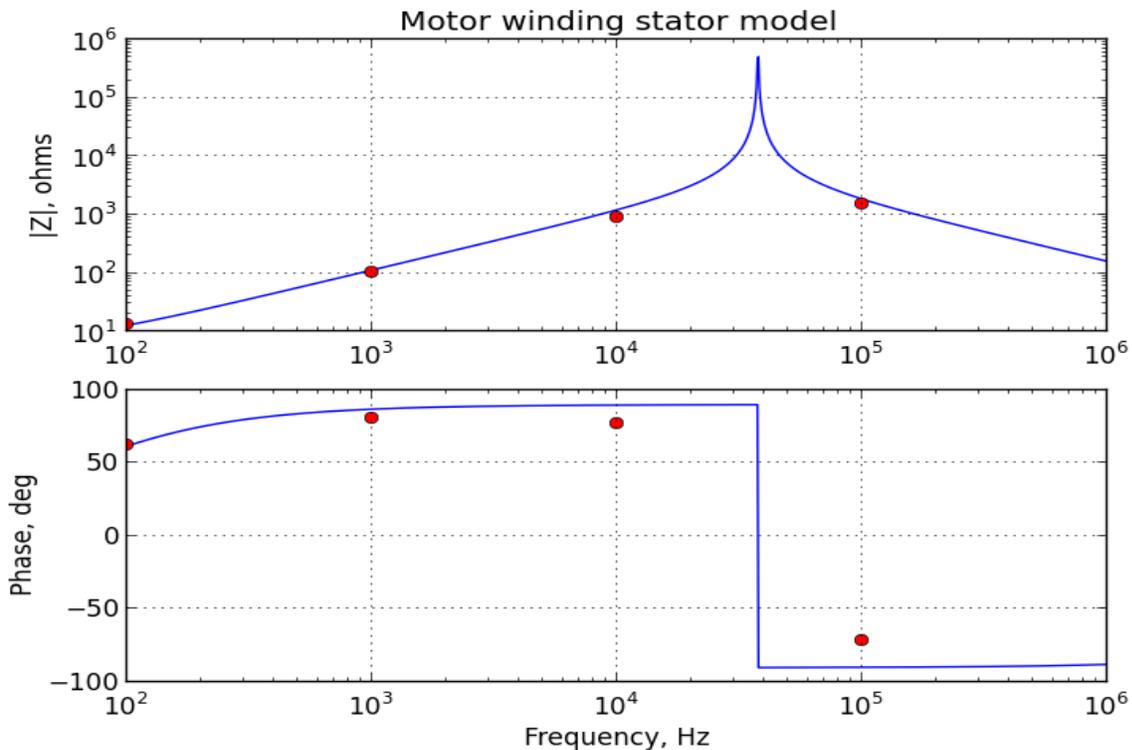


Figure 28

This lumped parameter model appears to predict the the measured behavior fairly well and would be a good starting point for a better model.

Regardless of whether we have a good model of the equivalent circuit or not, the LCR meter measures the impedance, then calculates the requested parameters from the measured impedance. The measured 100 kHz impedance is $1481 \Omega \angle -71.56^\circ$ and this phasor in rectangular coordinates is $468 - 1404j$ ohms. Comparing the imaginary part to the impedance relationship $\mathbf{Z} = R_s + j\omega L_s$ for inductors, we would calculate the series model inductance as:

$$L_s = \frac{\text{Im}(\mathbf{Z})}{\omega} = \frac{-1404}{2\pi 10^5} = -2.23 \text{ mH}$$

i.e., a negative inductance and exactly what was measured by the LCR meter.

Thus, an apparently unphysical measurement (e.g., a negative capacitance or inductance) may be an **artifact of the assumed physical model**. In this example's case, the measurement of the series inductance L_s at 100 kHz resulted in a negative inductance. We showed that the model in Figure 27 fit the experimental data fairly well. However, the L_s measurement of the LCR meter at 100 kHz forced the series model in Figure 6 to fit the data. The only way this model of a resistor and inductor in series could be made to fit the measured impedance with a negative phase angle would be if the inductance was negative.

Some key points:

- ◆ When things don't make sense, examine the impedance measurement.
- ◆ Don't assume an LCR measurement is wrong, even if it gives unphysical measurements -- investigate what is going on.
- ◆ The equivalent circuit model you use can have a big impact on how you interpret data.
- ◆ A negative inductance probably means you are measuring a capacitance. A negative capacitance probably means you are measuring an inductor.

As an aside, there is one measurement that you can get with a digital multimeter that is an unphysical measurement: a negative DC resistance. This measurement means either your multimeter is broken or you're making a measurement with a DC bias present in the circuit you're measuring. Reverse the leads, measure again, and average the two measurements to get the correct resistance measurement.

Why can't I get a stable reading?

Occasionally an LCR meter will frustrate you because it won't give you a stable reading. A first step to understanding why is to measure the impedance and observe what happens. If the impedance magnitude or phase won't settle to stable values, none of the parameters computed from the impedance such as R_s , R_p , C_s , C_p , L_s , L_p , D , Q , or θ will either. Some possible causes are the following:

Too much noise: There could be too much noise, especially for high impedances where the associated currents are small. Remember that to measure the impedance, the meter needs to apply a known voltage and measure the current, along with the phase angle between the current and the voltage. These low current levels may be influenced by extraneous sources of noise and therefore give unstable readings. You can try testing at a different frequency and extrapolate the results to the frequency of interest, but this can be a dubious practice in the face of unknown parasitic impedances or circuits/components that are not well-modeled by the simple equivalent circuits used by LCR meters. If you're in an electromagnetically noisy environment, try making the measurement in a different environment or if this is not possible, try using various electromagnetic shielding methods

(e.g., Faraday cage, Permalloy shields, etc.). If you're using leads, change to leads made from coaxial cables and use guarding to reduce the effects of noise (see **3-wire measurements and guarding**). Another solution may be to measure the impedance with a different LCR meter that uses a different measurement method because it might not be so sensitive to the measuring conditions.

The component is exhibiting a complicated behavior: The impedance measurement might not stabilize due to a complicated material property of the component. These types of instabilities may manifest themselves by giving continuously increasing or decreasing values, then stabilizing after a period of time. When this happens with capacitors, the effect may be caused by dielectric absorption or other properties of the dielectric. When it happens with inductors, it may be related to some magnetization property of the inductor's core¹⁰. In both cases, the behavior can be caused by the complicated electric or magnetic polarization behavior of dipoles and multipoles in the crystal lattices of real materials.

You are trying to measure a component that is near or beyond the meter's measurement limits: Capacitors that are larger than the meter's ability to measure may make the meter's display freeze. See **This capacitor is too large to measure** for some more information on this problem.

This inductance doesn't measure correctly

Some manufacturers specify the operation of an inductor under a DC bias. This DC bias can position the operating point at a particular point on the hysteresis curve of the core material. To reproduce the measurements made by the manufacturer, you'll want to ensure the inductor's inductance is measured at the bias conditions specified by the manufacturer. Check your LCR meter's manual to see if it is capable of making inductance measurements while a DC bias current is supplied to the inductor.

Another possibility is that you're trying to measure a component while it's installed in a circuit. This can be done for some components, especially components that are low impedance compared to those around them. However, the LCR meter sees the whole circuit as an impedance, so you may not get the true value of the component. The only way to know is to remove the component from the circuit. This means desoldering a surface mount device or clipping a lead on a device with leads.

This capacitor is too large to measure

Modern large capacitors may have capacitance values beyond the measurement capabilities of an LCR meter. If you need to measure many of these accurately, it may be worth your while to find an instrument that is rated to handle them. However, if it's only an occasional need, there may be other ways to measure the capacitance. Here are some ideas to explore:

1. Use a suitable low-value resistor and measure the time constant of the resulting RC network.
2. Start with a discharged capacitor. Apply a constant current to the capacitor using a DC power supply and time how long the current is applied. Then measure the voltage immediately after the current is turned off. The capacitance is the current in A multiplied by the time in seconds divided by the voltage in volts. Since a digital multimeter typically uses a constant current source to measure resistance, you can use an ohmmeter measurement with a stopwatch to perform this capacitance measurement. Measure the magnitude of the current source first.
3. You may want to consult IEC standards 62391-1 and 62391-2 for standardized methods of measuring large capacitors.

Note: Dielectric absorption with large capacitors can provide measurement challenges. Make sure you start with a capacitor that has been thoroughly discharged per the manufacturer's specifications.

¹⁰ If it happens with an air-core inductor, it may lead you to believe that the LCR meter may not be working correctly or you're measuring near the meter's physical measurement capabilities.

Glossary and symbols

A symbol in **this color** represents a complex quantity (phasor). Click on the links to go to the relevant section in the document.

B_p	Parallel susceptance
G_p	Parallel conductance
$ Z $	Magnitude of impedance
L_s	Series inductance
L_p	Parallel inductance
C_s	Series capacitance
C_p	Parallel capacitance
R_p	Parallel resistance
R_s	ESR (equivalent series resistance)
AC	Alternating current. While it refers to current, the term is used as a modifier to any electrical parameter that varies with time (whether that variation is sinusoidal or not).
admittance	The reciprocal of impedance .
B	Susceptance
C	Capacitance
capacitance	A measurement that often characterizes the amount of charge stored in capacitors. The standard equation for capacitance is $C = Q/V$, where C stands for capacitance, Q is the charge on the parallel plates, and V is the voltage across those plates. It's generally measured in the unit, Farad (F).
complex number	A pair of numbers with a defined algebra (i.e., they are a mathematical field). They have proven to be useful in modeling the behavior of sinusoidal electrical quantities that require the notion of amplitude and phase. Part of their usefulness results from Euler's theorem relating the complex exponential function to the trigonometric functions.
conductance	The imaginary part of the admittance .
D	Dissipation factor
DC	Direct current. While it refers to current, the term is used as a modifier to any electrical parameter that does not vary with time.
DCR	DC resistance
dissipation factor	The ratio D of a component's resistance to its reactance; convention uses the dissipation factor for capacitors and the quality factor Q for inductors.
DUT	Device under test. This is usually used to refer to the component or circuit being measured by the LCR meter.

G	Conductance
guard	A guard is an electrical measurement technique used to reduce the effect of common mode currents, which can add uncertainty to measurements.
impedance	Opposition to electrical current flow. Defined to be the voltage divided by the current.
inductance	A measurement that is defined in terms of emf, electromotive force, that is generated to oppose any change in current. The unit for measurement is in Henry (H).
L	Inductance
open/short calibration	A measurement of an open and a short used by an LCR meter to compensate for measurement leads and fixtures. See Open/short calibration for more details.
phasor	A complex number used to represent the amplitude and phase of a sinusoidal quantity at a specified frequency. Phasors are useful in the analysis of the steady state behavior of circuits because they can replace the solution of differential equations with the algebra of complex numbers.
Q	Quality factor
quality factor	The ratio Q of a component's reactance to its resistance; convention uses the quality factor for inductors and the dissipation factor D for capacitors.
reactance	The imaginary part of an impedance when the impedance is expressed in rectangular coordinates.
resistance	A measurement that indicates the amount of current given a potential difference. The standard formula to compute this measurement in electronic circuits is $R = V/I$, and the unit is ohms, often indicated by the Greek symbol omega (Ω).
rotor influence check	Measuring the inductance of an induction motor's winding(s) as a function of rotor angle. Plots of this information can give subtle clues about the health of the motor.
sinusoid	A waveform with the shape of a sine wave. It is characterized by the equation $A \cos(\omega t + \delta)$ where A is the amplitude, ω is the angular frequency, and δ is the phase.
susceptance	The imaginary part of the admittance .
$\tan \delta$	A number numerically equal to the dissipation factor. The angle δ is the complement of the phase angle θ of an impedance.
Y	Admittance , a phasor.
Z	Impedance , a phasor.
θ	Phase angle of impedance
ω	Radian frequency in radians per second. Calculated from the frequency f in Hz by $2\pi f$.

References

- Bethel, N. (n.d.). *Identifying motor defects through fault zone analysis*. ReliablePlanet.com. Retrieved Jul 30, 2013, from <http://www.reliableplant.com/Read/4288/motor-defects-fault-zone>.
- Callegro, L. (2013). *Electrical Impedance: Principles, Measurement, and Applications*. New York: CRC Press.
- Feynman, R., Leighton, R., and Sands, M. (1964). *The Feynman Lectures on Physics*. Volumes 1-3. Addison-Wesley.
- Grover, F. (2004). *Inductance Calculations*. Dover Publications. (Original work published 1946).
- Hemenway, C. and Caulton, M. (1962). *Physical electronics*. Wiley.
- Kundert, K. (2008, June). Modeling dielectric absorption in capacitors. Version 2d. *The Designer's Guide Community*. From <http://www.designers-guide.org>.
- McKinnon, D. and Smolleck, H. (2004). *Influence of rotor residual flux on the measurement of inductance and its possible use as an impending fault indicator*. PdMA Corporation. From http://www.pdma.com/pdfs/Articles/Influence_of_Residual_Flux_on_the_Measurement_of_Inductance.pdf.
- Rose, R., Shepard, L., and Wulff, J. (1966). *The structure and properties of materials, vol. 4: electronic properties*. Wiley.
- Steinmetz, C. (1916). *Theory and Calculation of Alternating Current Phenomena*. 5th ed. McGraw-Hill.
- Working Group 1 of the Joint Committee for Guides in Metrology. (2008). *Evaluation of Measurement Data - Guide to the Expression of Uncertainty in Measurement*. 1995 version with minor corrections. Bureau International des Poids et Mesures. From <http://www.bipm.org/en/publications/guides/gum.html>.
- Yavorsky, R. and Detlaf, A. (1975). *Handbook of Physics*. 2nd ed. MIR Publishers.