



Capacitance and Inductance Measurements Using an Oscilloscope and a Function Generator

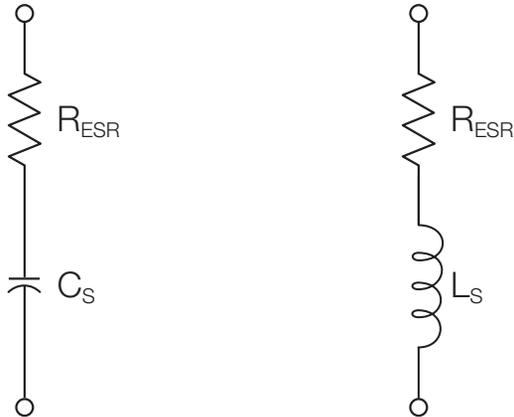
Application Note

Most labs have an ample supply of DMM's for measuring DC resistance, but when it comes to measuring inductance, capacitance and impedance, it is not always easy to find an LCR meter.

LCR meters operate by applying an AC voltage to the device under test, and measuring the resulting current, both in terms of amplitude and phase relative to the

AC voltage signal. A capacitive impedance will have a current waveform that leads the voltage waveform. An inductive impedance will have a current waveform that lags behind the voltage waveform. Fortunately, if you have an oscilloscope and a function generator in your lab, you can use a similar technique to make multi-frequency impedance measurements with good results. This approach may also be adapted for use as an instructional lab exercise.

Application Note



Capacitive

Figure 1. Impedance modeled as a capacitor or inductor with an equivalent series resistance.

Inductive

What is Impedance?

Impedance is the total opposition to current flow in an alternating current circuit. It is made up of resistance (real) and reactance (imaginary) and is usually represented in complex notation as $Z = R + jX$, where R is the resistance and X is the reactance.

Real-world components are made up of wires, connections, conductors and dielectric materials. These elements combine to make up the impedance characteristics of the component, and this impedance changes based on the test signal frequency and voltage level, the presence of a DC bias voltage or current and environmental factors such as operating temperatures or altitude. Of these potential influences the test signal frequency is often the most significant factor.

Unlike ideal components, real components are not purely inductive or capacitive. All components have a series resistance, which is the R parameter in its impedance. But they also have multiple contributors to their reactance. For example, a capacitor has a series inductance that becomes more apparent at high frequencies. When we measure a real capacitor, the series inductance (ESL) will impact the capacitance reading, but we won't be able to measure it as a separate, distinct component.

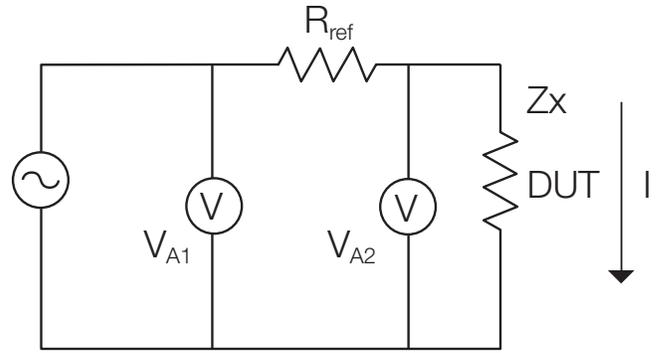


Figure 2. The I-V method test circuit.

Impedance Measurement Methods

The I-V method described in this application note is just one of many methods for measuring impedance. Others include the Bridge Method and the Resonant Method.

The I-V method uses the voltage and current value across the device-under-test (DUT) to calculate the unknown impedance, Z_x . The current is measured by measuring the voltage drop across a precision resistor in series with the DUT as shown in Figure 2. Equation 1 shows how the circuit can be used to find Z_x .

Equation 1:

$$Z_x = \frac{V_{A2}}{I} = \frac{V_{A2}}{V_{A1} - V_{A2}} R_{ref}$$

Theoretical Accuracy

In this application note we will use a Tektronix AFG2021 arbitrary/function generator and a Tektronix MDO4000 Series oscilloscope to do the measurement. The AFG2021's bandwidth of 20 MHz is well-suited for this measurement. The MDO4000's DC gain accuracy is 2% at a 1 mV/Div setting and 1.5% at other vertical settings. As you can see in Equation 1, the oscilloscope's voltage measurement accuracy is the most critical factor in the total test accuracy.

Based on Equation 1, the theoretical accuracy of this measurement method should be about 4% at the MDO4000's 1 mV/Div setting and 3% at other settings.

Since the sample rate of the oscilloscope is much higher than the frequencies of the stimuli used in these tests, the error contributed by the phase measurements will be negligible.

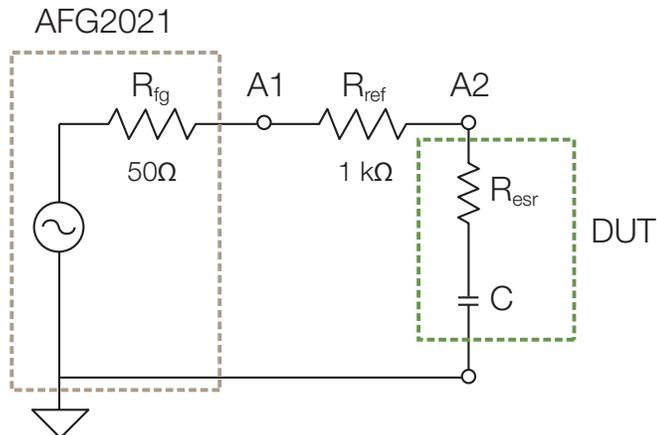


Figure 3. Test setup for evaluating a capacitor as in Example 1.

Test Example

The following two examples introduce capacitor/inductor/ESR measurement using an oscilloscope and a function generator.

Equipment used:

- AFG2021 arbitrary/function generator
- MDO4104C oscilloscope
- A 1 k Ω precision resistor
- Capacitors and inductors to be tested
- Two Tektronix TPP1000 voltage probes

For this application most oscilloscopes and function generators will give acceptable results since the test frequencies are below 100 kHz. However, we will take advantage of the measurement statistics on the MDO4000 Series in this example.

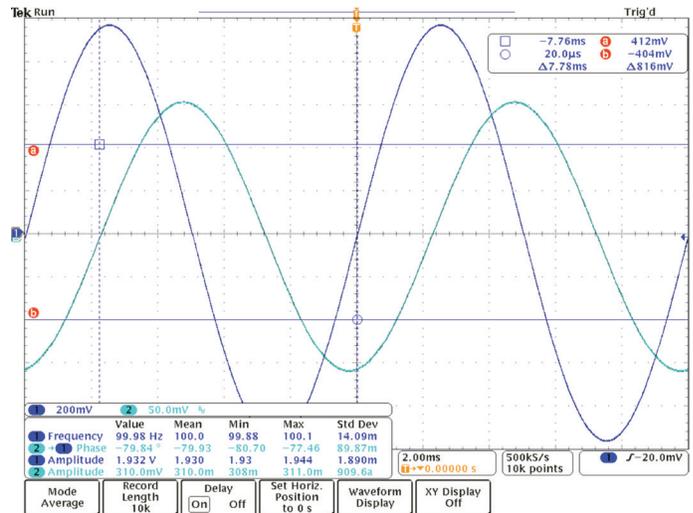


Figure 4. Voltage waveforms and measurements taken at nodes A1 and A2.

Example 1: 10 μ F ceramic capacitor

Set up the test circuit as shown in Figure 3. Note that R_{ESR} and C are both associated with the ceramic capacitor under test, and that R_{fg} is the 50 Ω output impedance of the function generator.

Set the function generator to output a 1.9 V amplitude, 100 Hz sine wave. You can use either the AFG2021's knob or keypad to set the voltage and frequency. Adjust the vertical scale setting of the oscilloscope to use as much of the display as possible – by using as much of the range as possible, you will improve the accuracy of your voltage measurements.

Use the oscilloscope to probe at nodes A1 and A2. Figure 4 shows the resulting waveform.

Select the oscilloscope's average acquisition mode and set the number of averages to 128. This will reduce the effects of random noise on your measurements. Set the oscilloscope to measure the channel 1 frequency, phase between channel 2 and channel 1, channel 1 amplitude, and channel 2 amplitude as shown in Figure 4. If your oscilloscope offers measurement statistics like the MDO4000 Series, record the mean values for your calculations. Otherwise, record the most recent values.

Application Note

From the measurement setup, we know:

Stimulus frequency, $f = 100 \text{ Hz}$

Precision Resistor, $R_{ref} = 1 \text{ k}\Omega$

From the measurements taken on the oscilloscope and shown in Figure 4:

Voltage amplitude measured at A1, $V_{A1} = 1.929 \text{ V}$

Voltage amplitude measured at A2, $V_{A2} = 0.310 \text{ V}$

Phase difference between voltage measured at A2 relative to A1, $\theta = -79.95^\circ$

Note that at node A1, the voltage has a phase angle of 0° , that is it is in phase with the function generator output. At A2 the voltage is shifted ahead by the phase angle θ .

The impedance of the capacitor under test can be found using Equation 1.

The impedance can be expressed in polar form, where the magnitude is given by:

Equation 2:

$$Z = \frac{V_{A2} R_{ref}}{\sqrt{V_{A1}^2 - 2V_{A1}V_{A2}\cos\theta + V_{A2}^2}}$$

The angle of the impedance is given by subtracting the two angles:

Equation 3:

$$\alpha = \theta - \tan^{-1} \frac{-V_{A2}\sin\theta}{V_{A1} - V_{A2}\cos\theta}$$

For the test in our example, we can use Equation 2 and Equation 3 to find the magnitude and angle of the impedance of the capacitor under test:

$$Z = \frac{(0.310)(1 \times 10^3)}{\sqrt{(1.929)^2 - 2(1.929)(0.310)\cos(-79.95^\circ) + (0.310)^2}}$$

$$Z = 163.193\Omega$$

$$\alpha = -79.95^\circ - \tan^{-1} \left(\frac{-0.310\sin(-79.95^\circ)}{1.929 - 0.310\cos(-79.95^\circ)} \right)$$

$$\alpha = -89.197^\circ$$

Now we can convert to the rectangular form of the impedance to find the resistance and capacitance.

$$Z = R_{ESR} - \frac{j}{2\pi f C}$$

$$Z = Z\cos\alpha + jZ\sin\alpha$$

Using the equations above, we can solve for the ESR and Capacitance of the DUT:

Equation 4:

$$R_{ESR} = Z\cos\alpha$$

Equation 5:

$$C = \frac{-1}{2\pi f Z\sin\alpha}$$

Using Equation 4 and Equation 5 we can calculate the ESR and capacitance for the capacitor under test:

$$R_{ESR} = 163.193\cos(-89.197)$$

$$R_{ESR} = 2.29\Omega$$

$$C = \frac{-1}{2\pi(100)(163.193)\sin(-89.197)}$$

$$C = 9.75\mu\text{F}$$

Capacitance and Inductance Measurements Using An Oscilloscope and A Function Generator

	by Scope/FG	by USB VNA	by LCR	by Scope/FG	by USB VNA	by LCR
Frequency	capacitance (uF)	capacitance (uF)	capacitance (uF)	ESR(ohm)	ESR(ohm)	ESR(ohm)
10Hz	10.3	10.4	N/A	28.3	32.8	N/A
30Hz	10.1	10.4	N/A	9.1	7.8	N/A
100Hz	9.8	10.3	10.22	2.4	3.2	2.3
300Hz	9.8	10.1	N/A	0.7	1.1	N/A
1kHz	9.7	9.8	9.96	0.3	0.3	0.21

Table 1. Example 1 comparison chart. The LCR manual says that it is of 0.05% accuracy and the USB VNA manual say it is of 2% accuracy.

Table 1 compares the results achieved with the oscilloscope and function generator to results achieved with a low cost VNA and a traditional LCR meter. The LCR meter used in this case only supported test frequencies of 100 Hz and 1 kHz which are common component test frequencies. You'll notice that the three methods correlate reasonably well.

Passive component values are specified with a particular frequency in mind, and LCR meters often have more than one test frequency for this reason. Table 1 shows the results using the oscilloscope/function generator combination at five different frequencies. You can see the effect of parasitic

inductance in the test circuit as the test frequency increases – the measured capacitance drops as the test frequency increases. See the section on "Measurement Range" for more information on test frequencies.

For the best results, you will need to keep the value of the precision resistor (R_{ref}) low enough to give a significant voltage waveform at node A2. The resistor should also be larger than 50 ohms or the function generator output impedance will factor into the measurement.

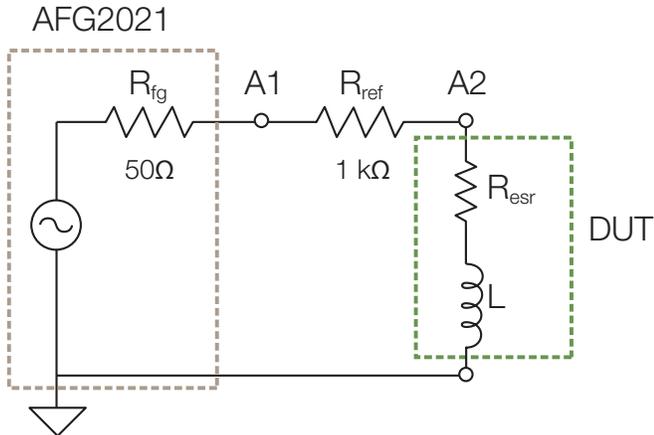


Figure 5. Test setup for evaluating an inductor as in Example 2.

Example 2: 10 mH inductor

The test circuit and procedure are almost identical to those used to test the capacitor in Example 1.

Use the function generator to output a 1.9 V amplitude 10 kHz sine wave. The signal is applied to the reference resistor and the inductor under test.

Use the oscilloscope to probe at nodes A1 and A2. Figure 6 shows the two resulting waveforms.

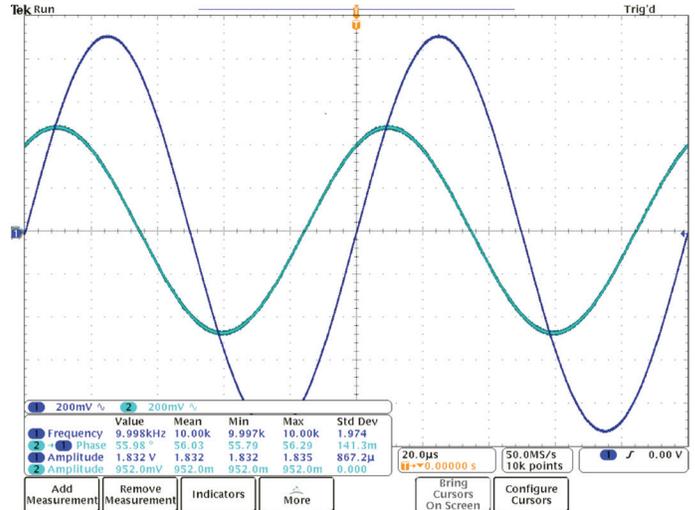


Figure 6. Voltage waveforms and measurements taken at nodes A1 and A2.

Select the oscilloscope's average acquisition mode and set the number of averages to 128. This will reduce the effects of random noise on your measurements. Set the oscilloscope to measure the channel 1 frequency, phase between channel 2 and channel 1, channel 1 amplitude, and channel 2 amplitude as shown in Figure 6. If your oscilloscope offers measurement statistics like the MDO4000 Series, record the mean values for your calculations. Otherwise, record the most recent values.

From the measurement setup, we know:

Stimulus frequency, $f = 10 \text{ kHz}$

Precision Resistor, $R_{\text{ref}} = 1 \text{ k}\Omega$

From the measurements taken on the oscilloscope and shown in Figure 6:

Voltage amplitude measured at A1, $V_{A1} = 1.832 \text{ V}$

Voltage amplitude measured at A2, $V_{A2} = 0.952 \text{ V}$

Phase difference between voltage measured at A2 relative to A1, $\theta = 56.03^\circ$

Note that at node A1, the voltage has a phase angle of 0° , that is it is in phase with the function generator output. At A2 the voltage is shifted ahead by the phase angle θ .

We can use the same equations to calculate the impedance of the DUT that we used to measure the capacitor In Example 1. The impedance can be expressed in polar form, where the magnitude and angle of the impedance are given by:

$$Z = \frac{(0.952)(1 \times 10^3)}{\sqrt{(1.832)^2 - 2(1.832)(0.952)\cos(56.03^\circ) + (0.952)^2}}$$

$$Z = 625.895\Omega$$

$$\alpha = 56.03^\circ - \tan^{-1}\left(\frac{-0.952\sin(56.03^\circ)}{1.832 - 0.952\cos(56.03^\circ)}\right)$$

Now we can convert to the rectangular form of the impedance to find the resistance and inductance

$$Z = R_{ESR} + j2\pi fL$$

$$Z = Z\cos\alpha + jZ\sin\alpha$$

Using the equations above, we can solve for the ESR and Inductance of the DUT:

Equation 6: $R_{ESR} = Z\cos\alpha$

Equation 7: $L = \frac{Z\sin(\alpha)}{2\pi f}$

Using Equation 6 and Equation 7 we can calculate the ESR and inductance for the inductor under test:

$$R_{ESR} = 625.895\cos(87.30)$$

$$R_{ESR} = 29.48 \Omega$$

$$L = \frac{625.895\sin(87.30)}{2\pi(10 \times 10^3)}$$

$$L = 9.95 \text{ mH}$$

	by Scope/FG	by USB VNA	by LCR	by Scope/FG	by USB VNA	by LCR
Frequency	Inductance (mH)	Inductance (mH)	Inductance (mH)	ESR(ohm)	ESR(ohm)	ESR(ohm)
10Hz	12	10.3	N/A	20.5	20.8	N/A
100Hz	10.1	10.4	10.31	20.6	20.9	20.9
1kHz	10.3	10.2	10.1	20.5	22	21.5
10kHz	10	9.8	9.76	29.8	31.5	29.4

Table 2. Example 2 comparison chart.

Again, Table 2 compares the results achieved with the oscilloscope and function generator to results achieved with a low cost VNA and a traditional LCR meter. The three methods correlate well.

Table 2 also shows the results using the oscilloscope/ function generator combination at four different frequencies. See the section on "Measurement Range" for more information on test frequencies.

Once again, you may need to experiment with the value of R_{ref} to get the best results.

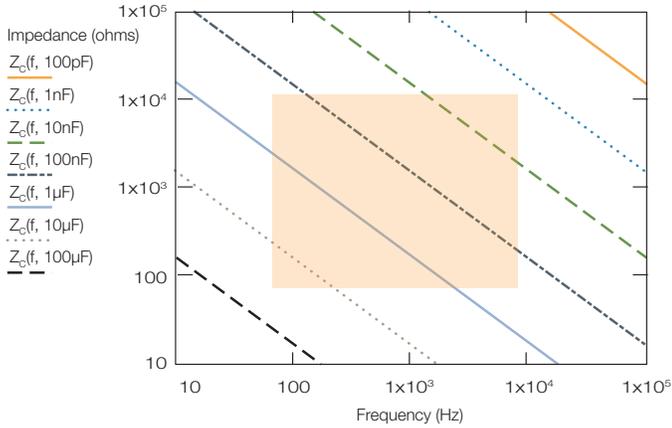


Figure 7. Capacitance/frequency box.

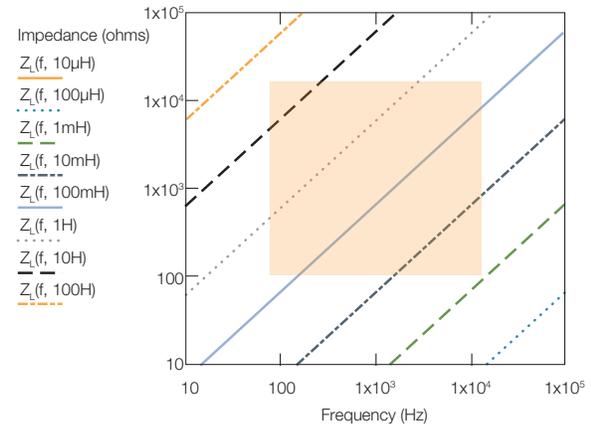


Figure 8. Inductance/frequency box.

Measurement Range

There are practical limits on the stimulus frequency and the DUT capacitor or inductor values for this impedance measurement method.

Figure 7 is a capacitance/frequency box. If a capacitance value and test frequency fall within the box, then you should be able to measure it. In the shaded region, the measurement accuracy will be about 3%, and outside the shaded area the accuracy drops to about 5%. These uncertainties assume that you've taken care to use the full display of the oscilloscope, averaged 128 cycles of the waveforms, and used the mean value of the amplitudes and phase to perform the calculations.

A similar inductance/frequency box is shown in Figure 8 for the inductor test.

Conclusion

If you don't have an LCR meter in your lab, or you want to demonstrate the behavior of capacitors and inductors under sinusoidal stimulus, an oscilloscope and a function generator can help you to do a simple, transparent impedance measurement. You can expect capacitance and inductance values with 3%-5% uncertainty. In order to take advantage of this method, you need only a function generator with good frequency and amplitude range, an oscilloscope with good specifications and the functions we've discussed, a few precision resistors, and a calculator or spreadsheet.

Contact Tektronix:

- ASEAN / Australasia** (65) 6356 3900
- Austria** 00800 2255 4835
- Balkans, Israel, South Africa and other ISE Countries** +41 52 675 3777
- Belgium** 00800 2255 4835
- Brazil** +55 (11) 3759 7627
- Canada** 1 800 833 9200
- Central East Europe and the Baltics** +41 52 675 3777
- Central Europe & Greece** +41 52 675 3777
- Denmark** +45 80 88 1401
- Finland** +41 52 675 3777
- France** 00800 2255 4835
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- India** 000 800 650 1835
- Italy** 00800 2255 4835
- Japan** 81 (3) 6714 3010
- Luxembourg** +41 52 675 3777
- Mexico, Central/South America & Caribbean** 52 (55) 56 04 50 90
- Middle East, Asia, and North Africa** +41 52 675 3777
- The Netherlands** 00800 2255 4835
- Norway** 800 16098
- People's Republic of China** 400 820 5835
- Poland** +41 52 675 3777
- Portugal** 80 08 12370
- Republic of Korea** 001 800 8255 2835
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