Designing an MLCC Distortion Meter: Voltage, Current, and DC Bias

Author: High SNR Lab | **Date:** August 2, 2026 | **Version:** 1

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The measurement path starts with a series circuit: a signal source, the MLCC under test, and a current-sense resistor. The source applies a sine wave, while two channels capture the voltage across the capacitor and the current through it.

Testing a Class 2 MLCC adds three constraints. The capacitor has to operate under DC bias, its voltage must be measured directly across its terminals, and the test setup must contribute less distortion than the device under test. Meeting those constraints requires a bias-injection network, an output buffer, and separate voltage and current signal paths.

The project is still in the design, calculation, and simulation phase. The functional architecture now defines the signal paths and the purpose of each major block; the circuit-level implementation and component values are still being refined.

Why Measure Voltage and Current at the Same Time?

A multilayer ceramic capacitor, or MLCC, is a two-terminal device. The generator setting U_G is not necessarily the voltage that appears across those terminals. Some of the applied voltage drops across the series impedances, and the output stage can introduce gain error, phase shift, and distortion. The instrument therefore records both the actual capacitor voltage U_C and the capacitor current I_C.

For an ideal linear capacitor, current is given by

$$i(t) = C \cdot \frac{du(t)}{dt}.$$

If the voltage is sinusoidal and the capacitance is constant, the current is sinusoidal as well. In a nonlinear dielectric, charge is no longer proportional to voltage, so the more useful relationship is $i(t) = \frac{dq(u)}{dt}$. The current can then contain additional harmonics even when the voltage remains close to a sine wave.

Source and driver harmonics appear first in U_C and then in I_C. A current-only measurement could incorrectly attribute them to the MLCC. Capturing U_C and I_C together gives the analysis the actual amplitude, phase, and waveform applied to the DUT.

Figure 1 shows the starting point. The generator produces U_G, the capacitor C is in series with the sense resistor R_L, and the same current I_C flows through both parts. R_G represents the series resistance of the generator path.

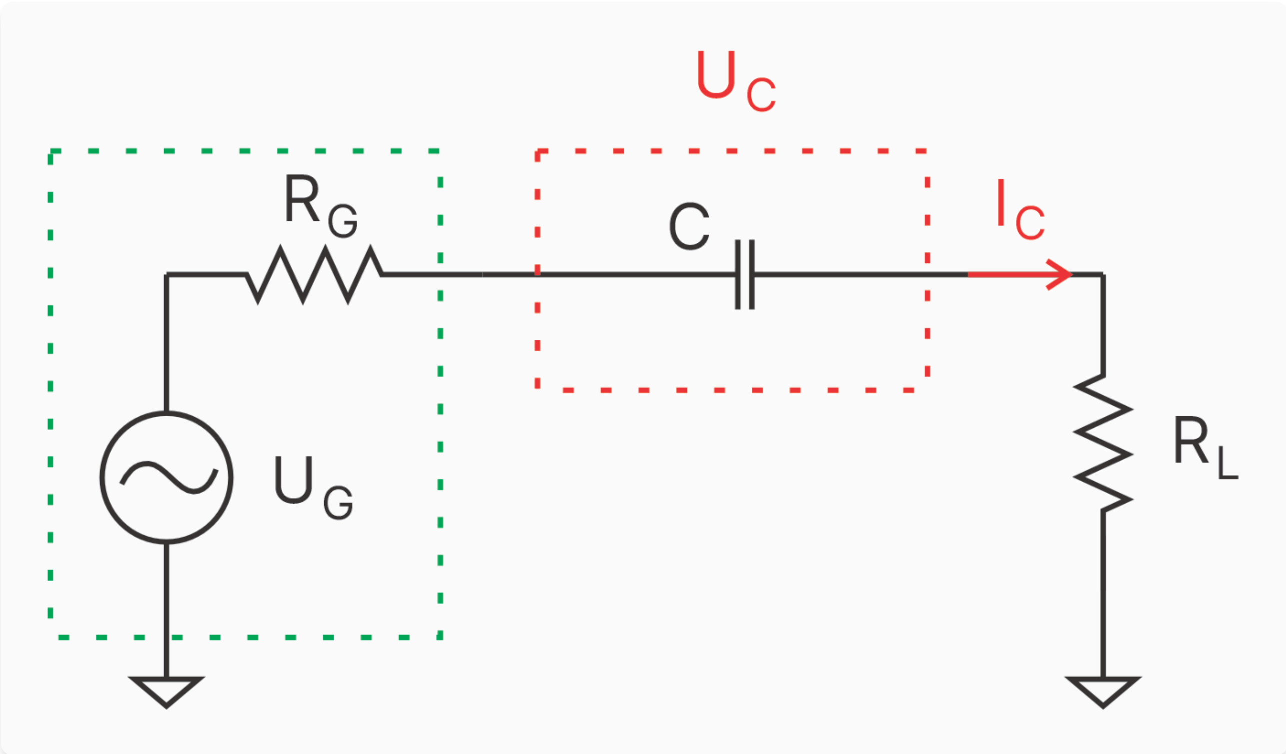

Figure 1. The starting circuit applies an AC test voltage and provides separate voltage and current measurements.

Figure 1 covers the zero-bias case. Characterizing a Class 2 MLCC also requires a controllable DC operating point without disturbing the source or either measurement channel.

Adding DC Bias Without Back-Driving the Source

The effective capacitance of a Class 2 ceramic capacitor depends on both DC and AC voltage. The DC bias sets the operating point on the nonlinear charge-voltage curve; the sine-wave amplitude determines how far the device moves around that point during each cycle. A zero-bias measurement captures only one part of that behavior.

The external bias voltage cannot simply be tied to the QA403 output. The source has to be isolated from DC, while the test circuit still needs enough AC drive current. The functional architecture assigns those jobs to an output buffer, the coupling capacitor CD , and the bias-injection network.

The buffer takes UG, presents a light load to the QA403, and supplies the current required by the test circuit. CD passes the AC stimulus while blocking the DC bias from the buffer and generator outputs. The bias supply $UDCB$ feeds the test node through R DCB. That resistor provides a DC charging path and makes the bias branch a high impedance at the test frequency, limiting AC current that would otherwise flow into the bias supply.

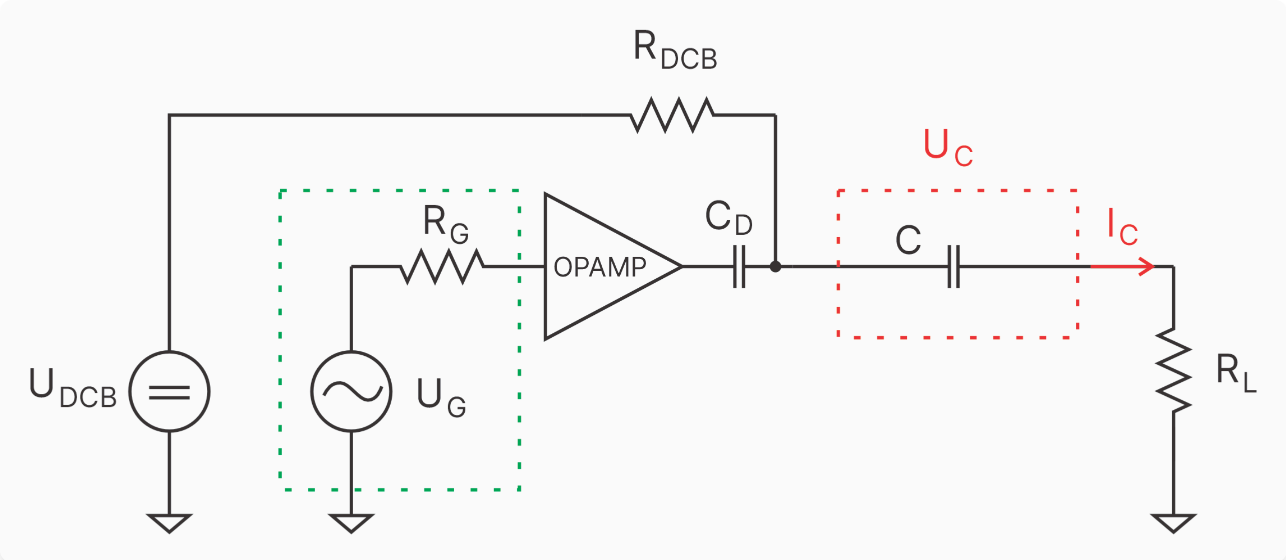

Figure 2. The buffer and C_D deliver the AC stimulus, while R_{DCB} injects DC bias at the test node.

The impedance of the R_{DCB} branch, including the bias supply's output impedance, must remain high enough across the measurement band. Otherwise, some of the AC drive current will be diverted into the bias supply instead of flowing through the DUT.

The coupling capacitor C_D is part of the measurement path. It sits in series with the DUT, withstands the applied DC bias, and contributes to the signal-path transfer function. Its capacitance, dielectric, voltage rating, frequency response, and residual nonlinearity all affect measurement accuracy.

Measuring the Capacitor Voltage Differentially

The lower terminal of the DUT connects to R_L, not directly to ground. The voltage across the MLCC is therefore

$$U_C = V_{TOP} - V_{BOTTOM}.$$

A single-ended measurement of the upper terminal would include the voltage across the current-sense resistor. The U_C channel must measure the difference between the two capacitor terminals.

Figure 3 shows C_1, C_2, and a differential buffer ahead of the voltage channel. C_1 blocks the DC bias present at the upper DUT terminal. C_2 makes the lower leg's transfer function symmetrical with the upper leg. Channel accuracy depends on matching the full complex impedance of the two legs across the measurement band—not just the nominal capacitance. Input resistance, phase shift, leakage, and voltage-dependent capacitance all matter.

Using the same part number for C_1 and C_2 does not guarantee identical behavior. The two capacitors can operate at different DC voltages, which can shift their effective parameters by different amounts. Any imbalance converts common-mode signal into a differential error that appears directly in the measured spectrum.

The triangle in Figure 3 represents the function of the voltage channel, not a committed circuit implementation. The QA403 already provides balanced, AC-coupled inputs. An external differential stage is useful when the design needs additional DC-fault protection, signal scaling, higher input impedance, or isolation. The detailed input-stage design will determine which of those functions are required.

Converting Capacitor Current Into a Voltage

If the U_C channel has sufficiently high input impedance, essentially all capacitor current flows through R_L. The shunt voltage is

$$U_{RL} = I_C \cdot R_L.$$

The following amplifier does not sense current directly. It buffers or amplifies U_{RL} and presents a suitable voltage to the analyzer. With amplifier gain A_I, the output is

$$U_I = A_I \cdot R_L \cdot I_C.$$

Figure 3 labels the current-channel output as $K \times I_C$, where `K` is the overall transimpedance. Its units are volts per ampere, or ohms. In the completed instrument, `K` includes R_L, the analog gain, and any calibration factor applied later in the signal chain.

Increasing R_L raises the current-channel signal and improves sensitivity, but it also increases the shunt voltage and reduces the voltage left across the MLCC. A smaller R_L interferes less with the test condition, at the cost of a lower signal and a more demanding low-noise amplifier. The shunt itself must be noninductive and sufficiently linear with voltage and temperature; otherwise, it can generate harmonics of its own.

Using the QA403 as the Source and Acquisition Engine

The QA403 generates the test stimulus and records both measurement channels. One input receives the signal proportional to the actual capacitor voltage U_C; the other receives $K \times I_C$. Both waveforms and their spectra are then available from the same acquisition.

The U_C and $K \times I_C$ labels in Figure 3 refer to calibrated representations of the physical quantities. Coupling capacitors, input impedances, the current shunt, and the amplifiers all sit between the DUT and the acquired data. Calibration has to account for the amplitude and phase response of those elements.

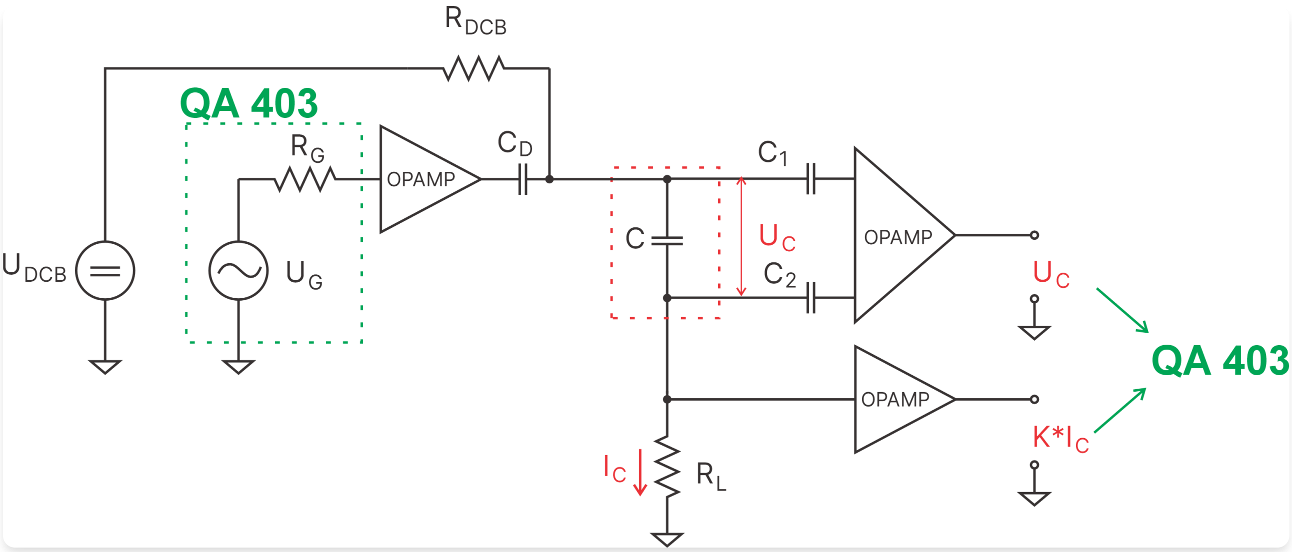

Figure 3. The QA403 provides the stimulus and records two calibrated signals: MLCC voltage and MLCC current.

Higher Frequency Demands More From the Driver

Capacitive reactance falls as frequency rises. For a fixed sinusoidal voltage, current through a linear capacitor increases approximately as

$$I_{C,RMS} \approx 2\pi f \cdot C_{EFF} \cdot U_{C,RMS}.$$

The driver will hold the requested MLCC voltage only while it can supply that current. As the circuit approaches the driver's limits, voltage drop across the output impedance, R_G , and R_L becomes more significant. Current limiting or insufficient slew rate can reduce the amplitude of U_C and distort its waveform.

The reactance of C_D also falls with frequency, so its contribution to the series voltage drop generally becomes smaller. At the low end of the band, C_D, C_1, and C_2 form high-pass networks with the surrounding resistances. At the high end, usable bandwidth is limited by output current, active-stage speed, and the measurement-channel response.

The Test Setup Must Be More Linear Than the DUT

The purpose of the instrument is to resolve small harmonic components. The output buffer, C_D, the bias network, the shunt, the differential voltage channel, and the current amplifier can all generate distortion. If their contribution is comparable to the MLCC's contribution, the analyzer measures the combined test setup rather than the capacitor alone.

Before comparing MLCCs, the setup needs a baseline. That means measuring its noise and residual distortion, checking it with a suitably linear reference device, and characterizing the amplitude and phase response of both channels. Those measurements will become a separate calibration procedure.

DC bias also introduces safety requirements. Every coupling and protection component needs an adequate voltage rating, and the QA403 inputs must remain within their allowable limits. Stored charge must be discharged in a controlled way after a test. Protection circuitry must also keep an output-buffer or bias-supply fault from reaching the analyzer or DUT; C_D alone is not a complete protection system.

Functional Blocks and Error Budgets

The functional design separates four jobs: generating the AC stimulus, injecting DC bias, measuring the voltage across the DUT, and converting capacitor current into a second measurement voltage. Each path can now be assigned its own level range, bandwidth, error budget, and residual-distortion target.

The original series loop—the source, the MLCC, and the shunt—remains the center of the instrument. The buffer and C_D place the AC stimulus on top of the DC operating point. The U_C channel measures voltage directly across the DUT, and the current channel produces $K \times I_C$. Measurement accuracy ultimately depends on how well those paths work together and how well they are calibrated.

In the next engineering note, I will take a closer look at the input circuits: their transfer functions, component selection, matching, protection, and simulation.

References

- Murata: The voltage characteristics of electrostatic capacitance
- Murata: Heat-generation characteristics of capacitors and measurement methods

- QuantAsylum: QA403 Audio Analyzer