QuadTech

Application Note

Calibration of 7000 Series Precision LCR Meters

Ever consider just how a precision impedance meter is calibrated? How the accuracy values are attained or what is meant by the uncertainty? What is the method to this measurement madness? Examine this discussion of the 7000 Series calibration procedure for information on basic calibration principles, zero correction and instrument calibration. Also discussed is the thought process and method of calibrating the master cal kit. An instrument's calibration is only as accurate as the calibration of the reference standards used to perform that calibration.

Calibration: Procedure to maintain an instrument's measurement accuracy. To check, adjust or systematically standardize the graduations of a quantitative measuring instrument*.

Accuracy: The difference between the measured value or reading and the true or accepted value. The accuracy of an LCR meter is usually given as a +/- percentage of the measured value for primary parameters (L, C, R) and +/- absolute value for secondary parameters (D, Q, θ).

Uncertainty: The percentage (or absolute) value variation from a measurement standard. Example: A 95kΩ Resistance standard has a NIST-traceable value of 95.3kΩ with an uncertainty of +/- .0157%. Uncertainty is sometimes referred to as tolerance.

* American Heritage Dictionary, © 1976, Houghton Mifflin Company

Figure 1.0: 7000-09 Calibration Kit

Calibration

The 7000-09 Calibration kit containing 4 resistance standards, 1 open standard and 1 short standard is used to calibrate the 7000 Series instrument. The nominal calibration kit values are 24.9Ω, 374Ω, 5.97kΩ and 95.3kΩ for the resistance standards. Calibrations are made on all measurement ranges at several frequencies. These values are then entered into instrument memory. Refer to Figure 2.0 for connection diagram. Interpolation formulas are used for all values between the NIST calibrated frequencies. Instrument calibration is valid for one year.

Verification

After Calibration, each 7000 Series instrument's accuracy is verified using 11 capacitance standards, 4 inductance standards and other resistance standards. Each standard is connected to the instrument, measured automatically at many frequencies (some at 27 frequencies from 10Hz to 2MHz) and at many different test signal levels. A total of over 10,000 measurements are made in a little over 12 hours.

Instrument Accuracy

The basic accuracy specification states only the accuracy at optimum test conditions. Comprehensive accuracy formulas are detailed in the 7000 Series instruction manuals. The "AutoAcc" feature displays the accuracy for any specific measurement conditions on the instrument front panel. This accuracy does not include the uncertainty of the calibration standards used.

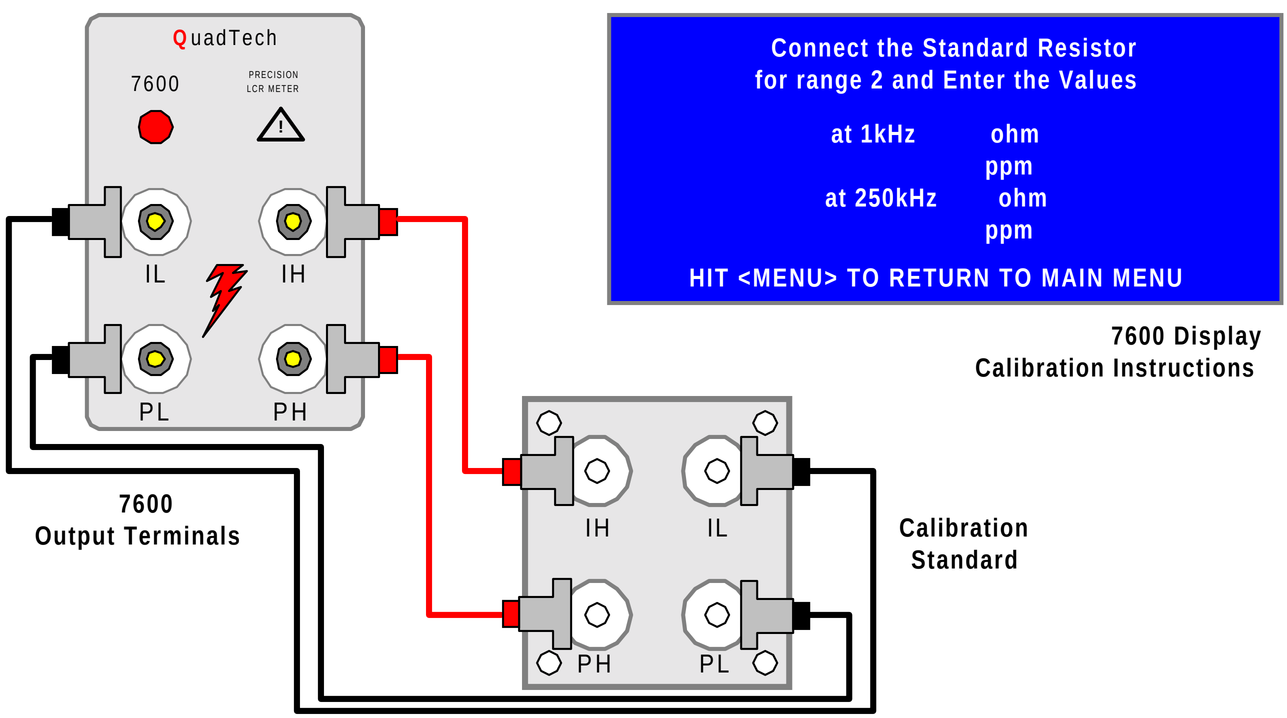


Figure 2.0: Connection of Cal Standard to 7600 Instrument

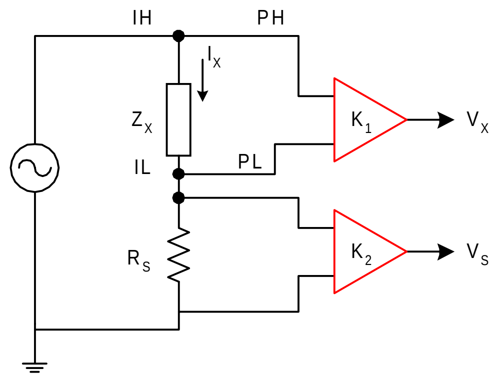
Calibration Principles

Method

The QuadTech 7000 Series Precision LCR Meters are calibrated using a set of four 4-terminal standard resistors, similar to those in the 7000-09 Calibration Kit shown in Figure 1. These standards are calibrated at low frequency against precision transfer boxes whose calibrations are derived from regular NIST calibrations of a GR1444 10kΩ standard. These standards are also calibrated at higher frequencies, for magnitude and Q, using special coaxial NIST-traceable standards. The accuracy of each instrument is also verified using capacitance, inductance and resistance standards whose values are derived from NIST measurements.

Measurement Circuit

Resistance standards are used to calibrate the 7000 Series instrument due to the fact that the meter itself derives the value of the unknown by measuring the complex voltage across the DUT and across an internal resistance standard connected in series. The complex ratio of the impedance of the DUT (Z_X) to the impedance of the standard (Z_{IS}) is Z_X/Z_{IS}. Refer to Figure 3. So if the impedance of the internal standard Z is known then the unknown impedance can be determined. Measuring the impedance of an external standard (Z_{EX}) provides the relationship Z_{EX}/Z_{IX} where the value of Z_{IX} is calculated if Z_{EX} is known. To obtain the values of C_X, L_X, D_X or Q_X from the value of Z_X it is necessary to know the precise frequency value. The 7000 Series instrument frequency is determined by a quartz oscillator and the actual measured value, and then entered into memory.



$$Z_X = \frac{V_X(R_S)}{V_S}$$

Figure 3.0: 7000 Series Measurement Circuit, Simplified

The same circuit is used to measure L, C, and R so the instrument can be calibrated with any standard of known value. QuadTech uses resistance standards for many reasons: calibration accuracy, stability, wide-range, compactness and the fact that their impedance is more constant with frequency. Four resistance standards are sufficient for all measurement ranges of the 7000 Series instrument. Although it is not necessary to use C or L NIST-traceable standards for *calibration*, they are used for *verification* to check for non-linearities, excess noise or other adverse measurement affects.

Interpolate, Model and Zero

There are more than four measurement ranges in the 7000 Series instrument due to the use of different gain amplification (K_1 and K_2) in the two measurement channels. The ratio of the complex voltages after amplification is $K_1 Z_{EX}/K_2 Z_{IS}$. K_1 and K_2 are the two voltage gains. Calibration calculations are made with all possible gain configurations.

It is impossible to calibrate an instrument at every value so we rely on the linearity of the instrument for measurements made between the actual calibrated values. Making verification measurements above and below the actual calibrated value checks the instrument linearity. Likewise, no instrument with thousands of possible test frequencies can be practically calibrated at each individual frequency. The known behavior of the instrument is used to interpolate between frequencies. The 7000 Series instrument is calibrated at several frequencies and tested at many more. Engineering verification tests have assured that this method is valid well within the specified accuracy.

Interpolation is also used with external standards. The external standards have better frequency characteristics than the effective internal standards (due to simple wiring and no voltage gain) so their values may be interpolated over wider frequency ranges. The Vishay film resistors used as standards were chosen for their good frequency behavior and stability. Thus NIST calibrations are necessary at just a few frequencies once it has been determined that the resistor behaves in accordance with the mathematical model based on said resistor's physical properties.

Air capacitors have a very simple model: their change in value with frequency is almost completely dependent on the series inductance. NIST uses air capacitors as the basis for their high-frequency calibrations. In calibrating its reference standards, QuadTech uses GR Type 1406 air coaxial capacitors for high frequency verification measurements plus the higher valued GR Type 1407 mica capacitor.

1407 Capacitor

Zero Corrections

Standards and components are measured using different connection methods. The 7000 Series instrument makes a 4-terminal measurement using BNC connectors. Some components are measured in test fixtures connected to BNC connectors. Calibration must be valid for all connections even though the hardware used may have different series resistance and inductance and shunt capacitance. To make sure the raw measured value is corrected for these series and shunt parameters, open circuit and short circuit measurements are made. These 'zero corrections' must be made each time the connection configuration (hardware) is changed.

Substitution measurements comparing 2-terminal coaxial standards to 4-terminal 7000 standards of similar value can be made if the proper zero corrections have been made for each standard. For ease of and concise connection, a 4-terminal open standard and a 4-terminal short standard are included in the 7000-09 Calibration kit.

Calibrating the Master Cal Kit Resistance Standards

Now the discussion takes a historical turn as to the method with which the four resistance standards of the master calibration kit were originally calibrated. To ensure the precision of the master (reference) calibration kit, true value measurements of the 4 resistors at DC & low frequency and high frequency were essential.

DC and Low Frequency Calibrations

QuadTech regularly sends a precision 10kΩ standard to NIST for precise DC resistance measurements. This value is scaled over a wide resistance range using a set of transfer boxes that have 12 resistors in series. DC substitution measurements are made using a special automated dc comparison bridge that calibrates each resistor and add the values of 10 resistors in series to get the next higher decade value. A similar method is used to scale the lower values.

The odd values of the master calibration kit are calibrated using series and parallel connection of the resistors in a transfer box to obtain values close to the calibration kit values (25Ω, 375Ω, 6kΩ, and 95kΩ) and then make substitution measurements. A QuadTech 1689 Digibridge is used to average many measurements and obtain better than 1 ppm precision at 100Hz. There is negligible change in values of the transfer boxes between dc and 100Hz. The estimate of uncertainty is 15 ppm for this calibration. The values are then checked at dc with a Daytron DMM with an accuracy specification of better than 20 ppm.

High Frequency Calibrations

QuadTech tested 16 coaxial NIST- traceable standards calibrated at several high frequencies when calibrating the master calibration kit. High frequency calibrations provide changes in the resistance values with frequency and the Q values, both of which should not change with time because they are largely independent of drift in the actual dc resistance value. Still, a set of resistors (R-1, R-2 and R-3 values) is sent annually to NIST for calibration.

That 25Ω Standard

NIST could not calibrate the 25Ω standard at the frequencies the 7000 Series instrument used so QuadTech investigated other methods for its calibration. All methods were traceable to NIST in some manner:

1. Measurements of several units on an Agilent 4284A that is calibrated with 50 termination and considered traceable by Agilent.
2. Measurements on a 1687 Digibridge that is calibrated with a 100pF GR Type 1406 coaxial air capacitor whose calibration is traceable.
3. Calculations on a 20Ω GR Type 1442 Resistor and on series combination of a 5Ω and 20Ω GR 1442 resistor standards based on the GR catalog of values of inductance and capacitance which are determined using traceable instruments and standards.
4. An old NIST (NBS) calibration of a 20Ω GR 1442 coaxial resistance standard made at 180Hz (NIST can calibrate this value at very high frequencies). This allowed QuadTech to get an inductance value close to that of the GR 1442 equivalent circuit and to show the change in resistance of this standard at 1MHz is negligible.
5. A parallel combination of two GR 900-W50 50Ω–terminations using a coaxial tee. The specifications for this termination indicate the change in resistance and the Q should be negligible.

Calibration of the 25Ω Standard

In addition, a 25Ω 4-terminal calibration kit standard was sent to NPL in England for measurements at intermediate frequencies. Rise time measurements were also performed from which resistance accuracy in the MHz range could be determined. All these measurements were within the QuadTech specified uncertainty values.

Putting all this information together, QuadTech ascertained that the change in resistance up to 1MHz was negligible for most units, particularly the parallel combination of 50Ω-terminations and the 20Ω GR 1442 standard. All Q measurements and calculations produced low Q values assuring the differences between equivalent series and parallel values were negligible [$R_P = R_S (1+Q^2)$].

The problem was in determining Q. The agreement between the methods employed was within +/- .0002 at 1MHz. The parallel termination method was assumed the best method because the Q value was only dependent on the capacitance of two open circuit terminations used for the zero measurement. Since this causes a Q value of only .000054 at 1MHz, the uncertainty must be very low. Today, to be safe QuadTech assigns an uncertainty of .0002 at this frequency and doubled it for the frequency equal to 2MHz.

The 7000 Series instrument was designed simply to make highly accurate impedance measurements over a wide frequency range. The original method of calibrating the master reference standards illustrates the extent to which QuadTech went to ascertain the precision of this instrument. The unit is capable of measuring 14 different parameters with 0.05% accuracy.

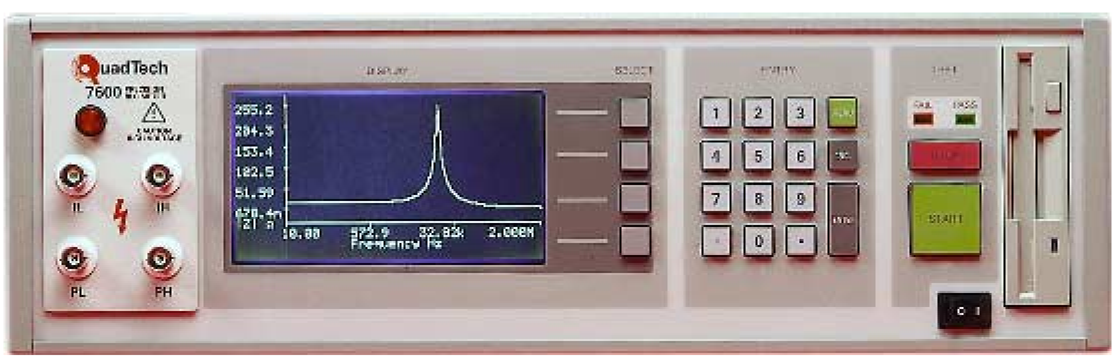


Figure 4.0: 7600 Precision LCR Meter

For complete product specifications on the 7000 Series Precision LCR meters or any of QuadTech's products, visit us at http://www.quadtech.com/products. Do you have an application specific testing need? Call us at 1-800-253-1230 or email your questions to info@quadtech.com.

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