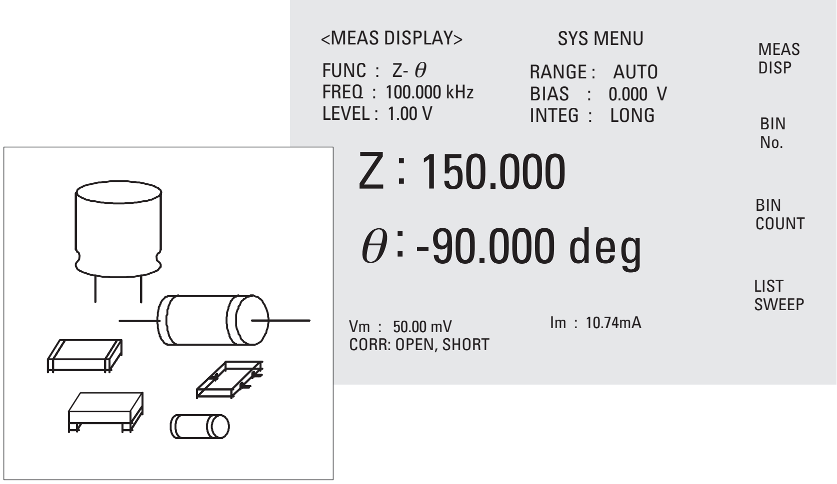
Keysight Technologies
8 Hints for Successful Impedance Measurements

Application Note

Characterizing Electronic Components
to Achieve Designed Circuit Performance



```
<MEAS DISPLAY>              SYS MENU                MEAS
                                                    DISP
FUNC  :  Z- θ          RANGE :   AUTO
FREQ  :  100.000 kHz   BIAS   :   0.000  V
LEVEL :  1.00 V        INTEG  :   LONG               BIN
                                                     No.
      Z : 150.000

                                                     BIN
      θ : -90.000 deg                                COUNT

                                                     LIST
      Vm  :  50.00 mV          Im  :  10.74mA        SWEEP
      CORR: OPEN, SHORT
```

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Impedance Measurements for Engineers

Impedance is measured using a variety of techniques. A particular technique is selected according to the test frequency, the impedance parameter to be measured and the preferred display parameters.

The Auto-Balancing Bridge technique is exceptionally accurate over a broad impedance range (mΩ to the order of 100 MΩ). The frequency range this technique can be applied to is from a few Hz to 110 MHz.

The IV and RF-IV techniques are also very accurate over a broad impedance range (mΩ to MΩ). These techniques can be applied from 40 Hz to 3 GHz.

The Transmission/Reflection technique is applied over the broadest frequency range (5 Hz to 110 GHz). This technique delivers exceptional accuracy near 50 Ω or 75 Ω.

LCR meters and impedance analyzers are differentiated primarily by display properties. An LCR meter displays numeric data, while an impedance analyzer can display data in either numeric or graphic formats.

The techniques employed by these instruments are independent of analyzer type, and can be RF-IV, IV or Auto-Balancing Bridge (depending on frequency).

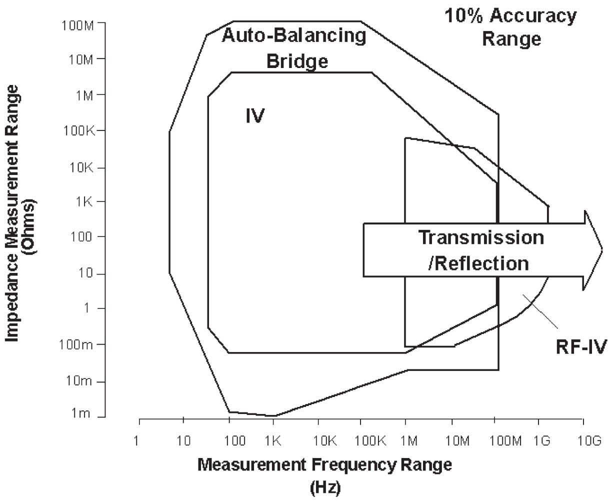


Figure 1. Accuracy Profile

Engineers perform impedance measurements for a variety of reasons. In a typical application, an electronic component used in a new circuit design is characterized. Normally, component manufacturers state only nominal impedance values.

Design decisions, as well as decisions affecting the production of the assembled product, depend to some degree on the impedance values attributed to the product's components. The performance and quality of the final product are therefore determined in part by the accuracy and thoroughness with which its components are characterized.

This application note provides helpful information for using the Auto- Balancing Bridge, IV and RF-IV techniques. Refer to Keysight Application Note 1291-1, *8 Hints for Making Better Network Analyzer Measurements* (literature number 5965-8166E) for information on the Transmission/Reflection technique.

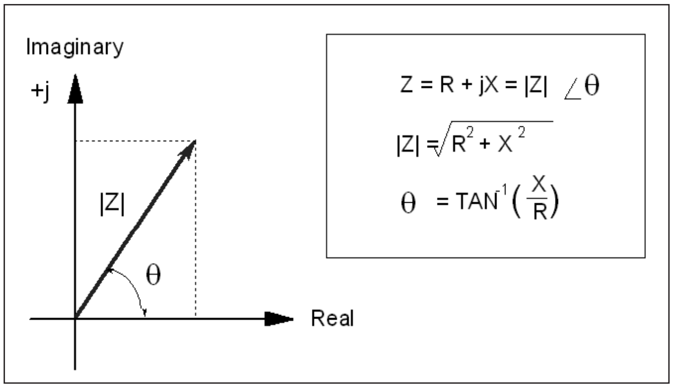
HINT 1.

Impedance Parameters

Impedance is a parameter used to evaluate the characteristics of electronic components. Impedance (Z) is defined as the total opposition a component offers to the flow of an alternating current (AC) at a given frequency.

Impedance is represented as a complex, vector quantity. A polar coordinate system is used to map the vector, where quadrants one and two correspond respectively to passive inductance and passive capacitance. Quadrants three and four correspond to negative resistance. The impedance vector consists of a real part, resistance (R), and an imaginary part, reactance (X).

Figure 2 shows the impedance vector mapped in quadrant one of the polar coordinate system.



$$Z = R + jX = |Z| \angle\theta$$

$$|Z| = \sqrt{R^2 + X^2}$$

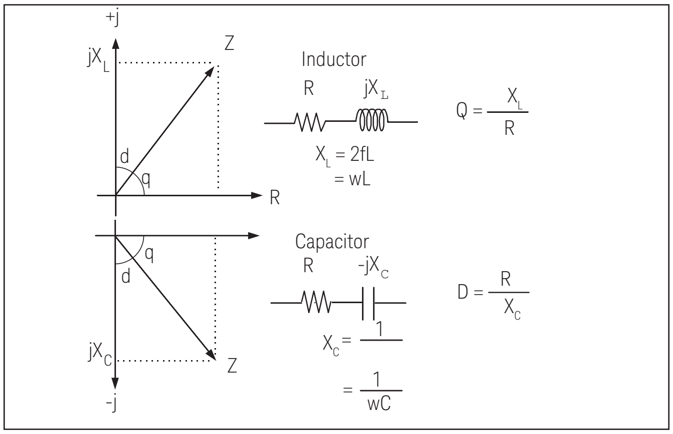
$$\theta = \mathrm{TAN}^{-1}\left(\frac{X}{R}\right)$$

Figure 2. Impedance Vector

Capacitance (C) and inductance (L) are derived from resistance (R) and reactance (X). The two forms of reactance are inductive (X_L) and capacitive (X_C).

The Quality Factor (Q) and the Dissipation Factor (D) are also derived from resistance and reactance. These parameters serve as measures of reactance purity. When Q is larger or D is smaller, the quality is better. Q is defined as the ratio of the energy stored in a component to the energy dissipated by the component. D is the inverse of Q. D is also equal to "tan δ", where δ is the dielectric loss angle (δ is the complementary angle to θ, the phase angle). Both D and Q are dimensionless quantities.

Figure 3 describes the relationship between impedance and these derived parameters.



$X_L = 2fL$
$= wL$

$Q = \frac{X_L}{R}$

$X_C = \frac{1}{}$
$= \frac{1}{wC}$

$D = \frac{R}{X_C}$

Figure 3. Capacitor and Inductor Parameters

HINT 2.

Measurements Depend on Test Conditions

A manufacturer's stated impedance values represent the performance of a component under specific test conditions, as well as the tolerance permitted during manufacture. When circuit performance requires more accurate characterization of a component, it is necessary to verify the stated values, or to evaluate component performance under operating conditions (usually different than the manufacturer's test conditions).

Frequency dependency is common to all components because of parasitic inductance, capacitance and resistance.

Figure 4 describes ideal and parasitic frequency characteristics of a typical capacitor.

Signal level (AC) dependency is exhibited in the following ways (see Figure 5):

- Capacitance is dependent on AC voltage level (dielectric constant, K, of the substrate).
- Inductance is dependent on AC current level (electromagnetic hysteresis of the core material).

The AC voltage across the component can be derived from the component's impedance, the source resistance, and the signal source output (Figure 6).

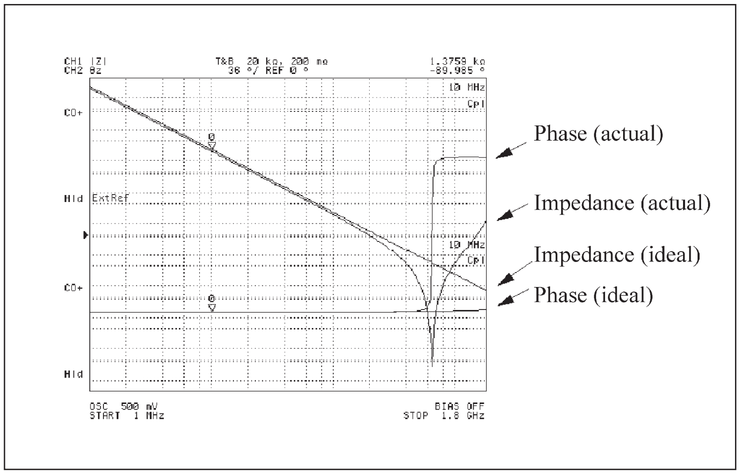
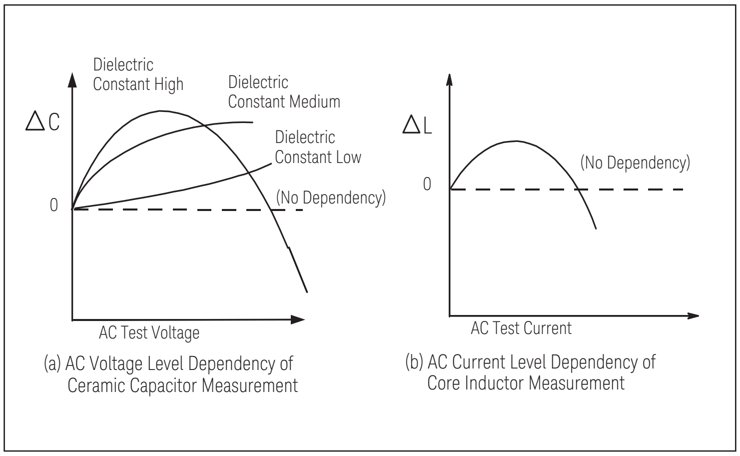


Figure 4. Frequency Characteristics of a Capacitor



(a) AC Voltage Level Dependency of Ceramic Capacitor Measurement

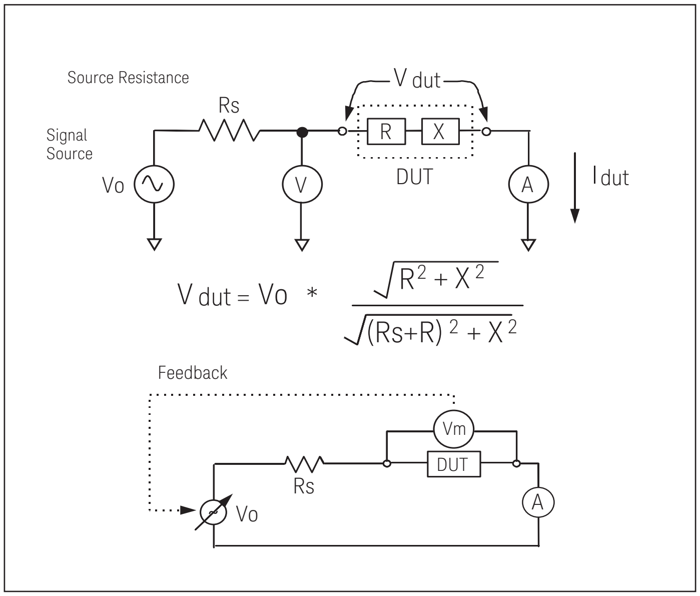
(b) AC Current Level Dependency of Core Inductor Measurement

Figure 5. Signal Level Dependency

An automatic level control (ALC) function maintains a constant voltage across the DUT (device under test). It is possible to write an ALC program for instruments that have a level monitor function, but not a built-in ALC.

Control of measurement integration time allows reduction of unwanted signals. The averaging function is used to reduce the effects of random noise. Increasing the integration time or averaging allows improved precision, but with slower measurement speed. Detailed explanations of these test parameters can be found in the instrument operating manuals.

Other physical and electrical factors that affect measurement results include DC bias, temperature, humidity, magnetic fields, light, atmosphere, vibration, and time.



$$V_{dut} = V_o * \frac{\sqrt{R^2 + X^2}}{\sqrt{(R_s+R)^2 + X^2}}$$

Figure 6. Applied Signal and Constant Level Mechanism

HINT 3.

Choose Appropriate Instrument Display Parameter

Many modern impedance measuring instruments measure the real and the imaginary parts of an impedance vector and then convert them into the desired parameters.

When a measurement is displayed as impedance (Z) and phase (θ), the primary element (R, C, or L) as well as any parasitics are all represented in the |Z| and θ data.

When parameters other than impedance and phase angle are displayed, a two-element model of the component is used. These two-element models are based on a series or parallel circuit mode (Figure 3-1), and are distinguished by the subscripts "p" for parallel and "s" for series (Rp, Rs, Cp, Cs, Lp, or Ls).

No circuit components are purely resistive or purely reactive. A typical component contains many parasitic elements. With the combination of primary and parasitic elements, a component acts like a complex circuit.

Recent, advanced impedance analyzers have an Equivalent Circuit Analysis Function that allows analysis of the measurement result in the form of three- or four-element circuit models (Figure 8). Use of this function enables a more complete characterization of a component's complex residual elements.

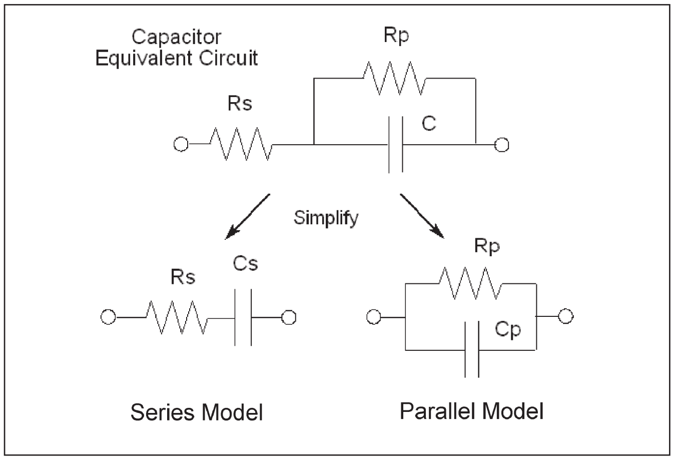


Figure 7. Measurement Circuit Mode

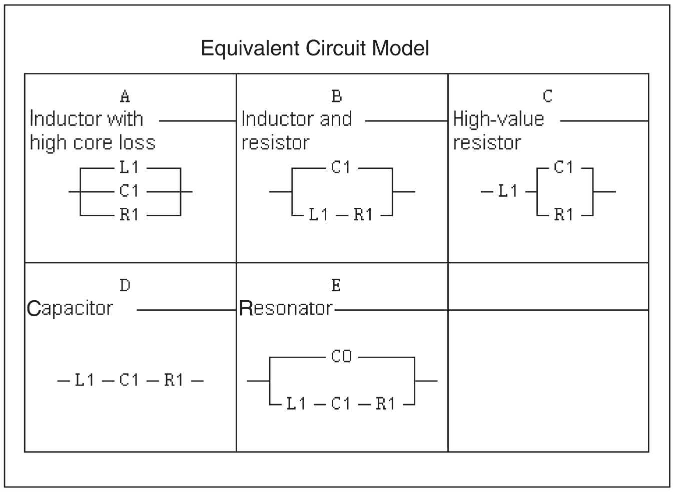


Figure 8. Equivalent Circuit Analysis Function

HINT 4.

A Measurement Technique Has Limitations

The most frequently asked question in engineering and manufacturing is probably: “How accurate is the data?”

Instrument accuracy depends on the impedance values being measured, as well as the measurement technology employed (see Figure 1).

To determine the accuracy of a measurement, compare the measured impedance value of the DUT to the instrument accuracy for the applicable test conditions.

Figure 9 shows that a 1 nF capacitor measured at 1 MHz exhibits an impedance of 159 Ω.

Instrument accuracy specifications for D or Q measurements are usually different than accuracy specifications for other impedance terms.

In the case of a low-loss (low-D/high-Q) component, the R-value is very small relative to the X-value. Small changes in R result in large changes in Q (Figure 10).

The measurement error is on the order of the measured R-value. This can result in negative D or Q values.

Be aware that measurement error includes error introduced by the instrument as well

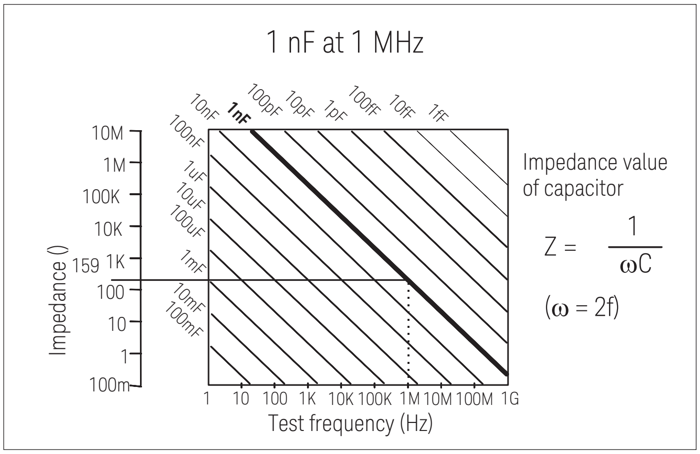


Figure 9. Capacitor Impedance and Test Frequency

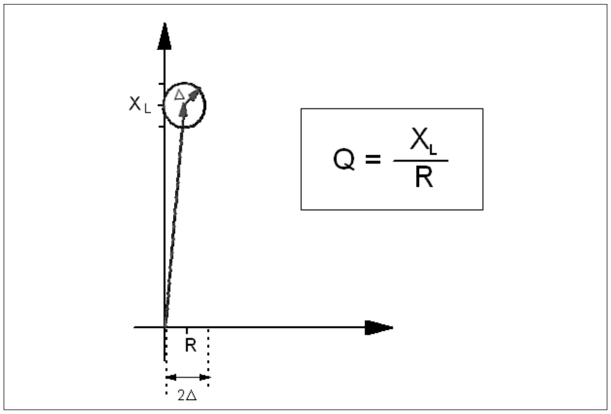


Figure 10. Concept of the Q Error

as by the test fixture.

HINT 5.

Perform Calibration

Calibration is performed to define a reference plane where the measurement accuracy is specified (Figure 11). Normally, calibration is performed at the instrument's test port. Corrections to raw data are based on calibration data.

A baseline calibration is performed at service centers for Auto-Balancing Bridge instruments such that the specified accuracy can be realized for a period of time (usually twelve months) regardless of the instrument settings. With these instruments, operators do not require calibration standards.

Baseline calibration for non-Auto-Balancing Bridge instruments requires that a set of calibration standards be used after instrument initialization and setup. This hint provides information that may be helpful when using calibration standards to establish calibration for these instruments.

Some instruments offer the choice of fixed-mode or user-mode calibration. Fixed-mode calibration measures calibration standards at predetermined (fixed) frequencies. Cali-bra-tion data for frequencies between the fixed, calibrated points are interpolated.

Fixed-mode calibration sometimes results in interpolation errors at frequencies between the fixed, calibrated points. At higher frequencies, these errors can be substantial.

User-mode calibration measures calibration standards at the same frequency points the user has selected for a particular measurement. There can be no interpolation errors associated with user-mode calibration.

It is important to recognize that the operator-established calibration is valid only for the test conditions (instrument state) under which calibration is performed.

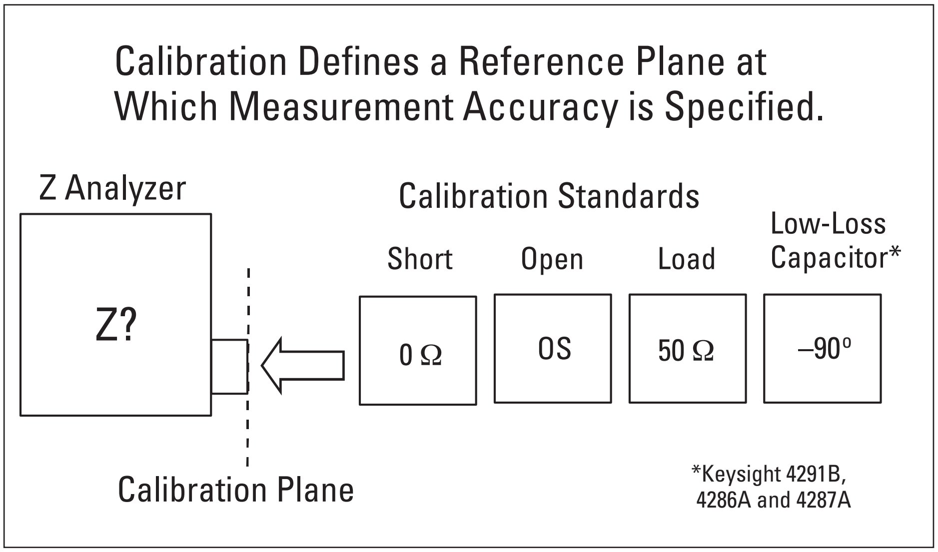


Figure 11. Calibration Plane

HINT 6.

Perform Compensation

Compensation is not the same as calibration. The effectiveness of compensation depends on the instrument calibration accuracy, therefore compensation must be performed after calibration has been completed.

When a device is directly connected to the calibration plane, the instrument can measure within a specified measurement accuracy. Since a test fixture or adapter is usually connected between the calibration plane and the device, the residual impedance of the interface must be compensated for to perform accurate measurements.

Additional measurement error introduced by a test fixture or adapter can be substantial. The total measurement accuracy consists of the instrument accuracy plus the error from sources that exist between the DUT and the calibration plane.

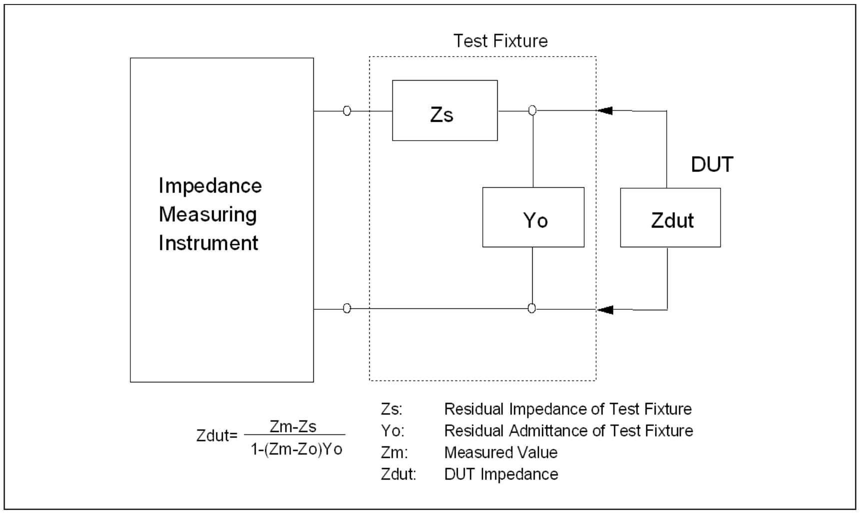
It is important to verify that error compensation is working properly. In general, the impedance value for an open condition should be greater than 100 times the impedance of the DUT. In general, the impedance value for a short condition should be less than 1/100 the impedance of the DUT.

Open compensation reduces or eliminates stray capacitance, while short compensation reduces or eliminates the unwanted resistance and inductance of fixturing.

When performing an open or a short measurement, keep the distance between the UNKNOWN terminals the same as when the DUT is contacted. This keeps parasitic impedance the same as when measurements are performed.

Perform load compensation when the measurement port is extended a non-standard distance, the configuration uses additional passive circuits/components (for example, a balun, attenuator, or filter), or when a scanner is used. The impedance value of the load must be accurately known. A load should be selected that is similar in impedance (at all test conditions) and form-factor to the DUT. Use a stable resistor or capacitor as the LOAD device.

It is practical to measure a load using open/short compensation and a non-extended fixture to determine the load impedance. The values measured can then be input as compensation standard values.



$$\mathrm{Zdut}=\frac{\mathrm{Zm}-\mathrm{Zs}}{1-(\mathrm{Zm}-\mathrm{Zo})\mathrm{Yo}}$$

Zs: Residual Impedance of Test Fixture
Yo: Residual Admittance of Test Fixture
Zm: Measured Value
Zdut: DUT Impedance

Figure 12. OPEN/SHORT Compensation

HINT 7.

Understanding Phase Shift and Port Extension Effects

Cable length correction, port extension, or electrical delay is used to extend or rotate the calibration plane to the end of a cable or the surface of a fixture. This correction reduces or eliminates phase shift error in the measurement circuit.

When the measurement port is extended away from the calibration plane (Figure 13), the electrical characteristics of the cable affect the total measurement performance. To reduce the resulting effects:

- Make measurement cables as short as possible.
- Use well-shielded, coaxial cables to prevent influence from external noise.
- Use low-loss coaxial cables to keep from degrading accuracy, since the port extension method assumes lossless cable.

A phase-shift-induced error occurs due to the test fixture, which can not be reduced using OPEN/ SHORT compensation.

When working in the RF region, calibration should be performed at the end of an extension cable. If calibration standards cannot be inserted, port extension can be used in this region for short and well-characterized distances.

When using the Auto-Balancing Bridge technique with non-standard cables or extensions, open/short/load compensation should be performed at the terminus of an extension or fixture. Auto-Balancing Bridge products use cable length compensation for standardized test cables (1, 2, or 4 meters). At the terminus of the standardized extension cable, the shields should normally be connected together.

Port extension in any form has limitations. Since any extension will contribute to losses in the measurement circuit and/or phase error, it is imperative that the limitations of the measurement technique be fully understood prior to configuring an extension.

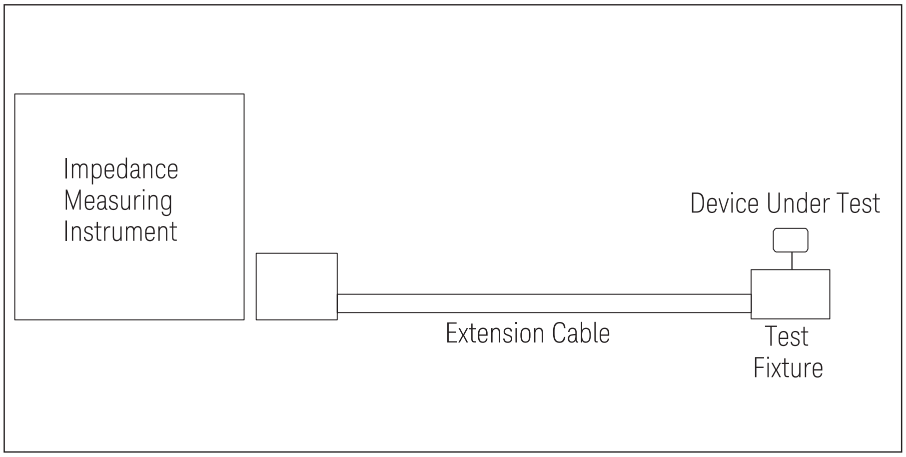


Figure 13. Measurement Port Extension

HINT 8.

Fixture and Connector Care

High-quality electrical connections insure the capability to make precise measurements. At every connection, the characteristics of the mating surfaces vary with the quality of connection. An impedance mismatch at mating surfaces will influence propagation of the test signal.

Attention should be paid to the mating surfaces of test ports, adapters, calibration standards, fixture connectors, and test fixtures. The quality of connections depends on the following:

- composition
- technique
- maintenance
- cleanliness
- storage

Composition

It has been said that a chain is as strong as the weakest link. The same is true for a measurement system. If low-quality cables, adapters or fixtures are used in a test system, the overall quality of the system is reduced to that of the lowest-quality interface.

Technique

The use of a torque wrench and common sense insures that damage does not occur when making repeated connections. Damage includes scratching and deformation of the mating surfaces.

Maintenance

Many mating surfaces are designed to allow for the replacement of parts that degrade with use. If a mating surface cannot be repaired, regularly scheduled replacement is advised.

Cleanliness

The use of non-corrosive/non-destructive solvents (such as de-ionized water and pure isopropyl alcohol) and lint-free wipes insures that the impedance at mating surfaces is not influenced by residual oils or other impurities. Note that some plastics are denatured with the use of isopropyl alchohol.

Storage

If a case is not provided with an accessory, plastic caps should be used to cover and protect all mating surfaces when not in use.

Keysight Technologies' Impedance Product Lineup

Keysight offers the widest selection of impedance measuring equipment for your applications. An overview of these instruments is given below. For more information, refer to the product literature listed at the end of this note.

LCR Meters

LCR meters can easily and accurately evaluate components such as capacitors, inductors, transformers and electromechanical devices. The ability of these instruments to apply specific measurement conditions (such as test frequency and signal level) is important in the R & D, production test and QA environments.

Impedance Analyzers

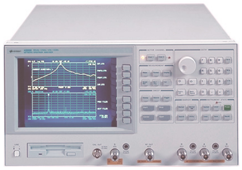
Keysight impedance analyzers can measure characteristic changes in component performance resulting from changes in specific measurement conditions. The characteristic changes in performance can be displayed in a graphical format. These analyzers provide sophisticated functions, such as markers and programming, which ease evaluation of measurement results. They also have features that enable characteristic evaluations for R & D, as well as reliability evaluations (including temperature characteristics) for QA purposes.

Network Analyzers

Network analyzers allow impedance measurements at RF and microwave frequencies using the Transmission/ Reflection technique. Their graphical displays have markers and programming functions that simplify the analysis of measurement results. Keysight network analyzers are suitable for both R & D and QA use.

Combination Analyzers

Combination analyzers from Keysight provide three capabilities—vector network, spectrum and impedance measurements—in one box. These instruments deliver broad functionality to engineers over a wide range of applications from circuit design to component evaluation.



Product Literature

1. LCR Meters, Impedance Analyzers, and Test Fixtures Selection Guide, literature number 5952-1430E.

2. RF Economy Network Analyzer, literature number 5967-6316E.

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