User's Guide

Impedance Measurement Handbook

1st edition

Introduction

This handbook describes settings and precautions that apply when using an impedance measuring instrument.

Impedance Measurement Handbook

1 Making high-precision measurements

There are several tricks to measuring impedance with a high degree of precision. There are two components of impedance precision: deviation (accuracy relative to the true value) and variability (stability of measured values). Each component requires that different factors be considered.

-1 Optimizing measurement conditions

Optimizing measurement conditions is an important part of making high-precision measurements. The following introduces the measurement conditions required when using an impedance measuring instrument.

(1) Frequency

Frequency is the most fundamental measurement condition for an impedance measuring instrument. Realistically, all electronic components exhibit frequency dependence, with the result that impedance values vary with frequency. In addition, the measurement precision of impedance measuring instruments varies with frequency and impedance value.

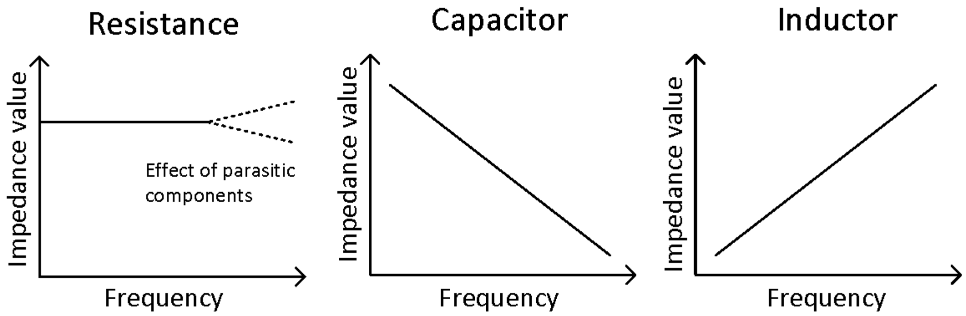

Figure 1. Frequency dependence of typical electronic components[1]

(2) Signal level

Impedance measuring instruments apply an AC signal that is output from the measurement terminals to the device under test (DUT). The level of the applied signal can be set as appropriate based on the DUT. In general, higher signal levels result in less variability in measured values, but it's necessary to consider whether the applied measurement signal will cause an electrical breakdown in the DUT.

For most impedance measuring instruments, the measurement signal level is defined in terms of the measurement terminals' open voltage. This corresponds to the open-terminal voltage (V) illustrated in Figure 2. In this case, the voltage applied to the DUT is affected by the output resistance of the signal source that is built into the impedance measuring instrument.

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[1] More accurately, capacitors and inductors exhibit a more complex type of frequency dependence due to the effects of parasitic components.

On the other hand, the impedance value of some electronic components varies with the measurement signal level. Measured values for capacitors (particularly ceramic capacitors) and inductors vary with the voltage across the DUT's terminals and the current flowing to the DUT, respectively. To evaluate the dependence of these components, it is necessary to use a constant-voltage (CV) mode, which maintains a constant voltage across the DUT's terminals, or a constant-current (CC) mode, which maintains the current flowing to the DUT at a uniform level. In addition, it is necessary to consider the effects of not only the measurement signal (AC) for these elements, but also the bias signal (DC).

See also: 1 -1(5) DC bias

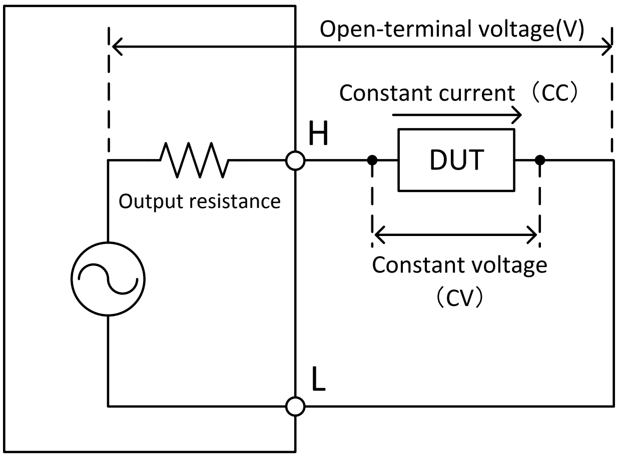

Figure 2. Difference in measurement signal level by mode

(3) Measurement speed

There is a trade-off between measured value variability and measurement time. Most impedance measuring instruments allow the user to select from among several measurement speeds.

Lower measurement speeds result in reduced measured value variability. To determine the appropriate measurement speed, it is necessary to consider the required level of precision and measurement time. Figure 3 illustrates the relationship between measurement speed and measured value variability.

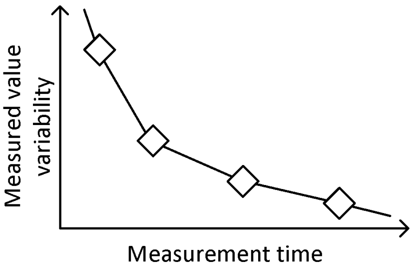

Figure 3. Relationship between measurement time and variability

(4) Measurement range

The measurement range is an important factor that affects measured value variability in all instruments, not just those used to measure impedance. The measurement range is selected based on the DUT’s impedance level.

It is recommended to use the auto range function when measuring an electronic component of unknown properties. This function automatically selects the appropriate range based on the measured impedance.

If you know the impedance value of the electronic component being measured, select the appropriate range using the hold range function. Use of this function yields shorter measurement times than the auto range function.

(5) DC bias

Measured values may exhibit variability due to the effects of the DC bias that is applied to the DUT. As illustrated in Figure 4, capacitance values for capacitors with level dependence exhibit variation depending on the DC bias voltage, while inductance values for inductors exhibit variation depending on the DC bias current. To evaluate DC bias dependence, it is necessary to use either the DC bias superposition function provided by the impedance measuring instrument or an external DC bias unit. Hioki provides both DC voltage bias units and DC current bias units.

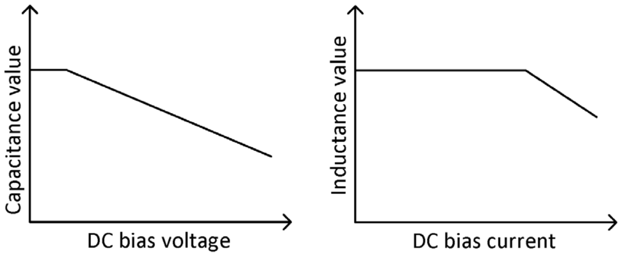

Figure 4. Example effects of DC bias

-2 Measuring level-dependent elements

When measuring an element whose characteristics vary with the signal level, it is necessary to develop a good understanding of the element’s characteristics in order to boost the reproducibility of measured values.

Even if the measurement signal levels are held constant, variations in frequency will result in variations in the voltage that is applied to, and the current that flows to, the DUT because the impedance values of capacitors and inductors vary with the frequency. To measure level dependence, it is necessary to check not the measurement signal level (open-terminal voltage), but rather the voltage and current that are applied to the DUT.

(1) Voltage dependence

Among ceramic capacitors, components with high dielectric constants are especially prone to the effects of voltage, with application of a voltage triggering variation in the effective capacitance. The recent trend toward miniaturization of ceramic capacitors has made it necessary to utilize high-dielectric-constant materials in order to achieve the simultaneous imperatives of compact size and high capacitance, resulting in especially pronounced voltage dependence.

There are several considerations that must be taken into account when measuring ceramic capacitors with a high dielectric constant. The effective capacitance when a DC voltage or AC voltage is applied to a capacitor is known as the component's DC bias characteristics or AC voltage characteristics, respectively, and the amount of variation differs depending on the element in question. Concerning DC bias characteristics that describe behavior when a DC voltage is applied to a capacitor, the effective capacitance decreases when the applied DC bias voltage increases, as illustrated in Figure 4. Components with a small amount of variation in capacitance when the applied voltage is varied are said to have good voltage dependence. Capacitance values for capacitors that are listed on product datasheets are measured while an AC voltage alone is applied to the capacitor. It is necessary to bear in mind the fact that the capacitance can decrease significantly in that region even if the value falls within the rated voltage.

The capacitance may vary by measuring instrument even when measuring the same capacitor. For the most part, the factors that account for this phenomenon arise because the applied voltage in fact varies, even if the set voltage is the same.

In fact, the signal level applied to the DUT is the value obtained by dividing the set signal source's output voltage by the DUT's impedance and the measuring instrument's output resistance, as illustrated by Figure 2. The voltage V_{DUT} applied to the DUT when the measurement frequency is f can be defined in terms of the output resistance Ro, the DUT capacitance C, and the signal source voltage Vo as follows:

$$V_{DUT} = \frac{\frac{1}{j \cdot 2\pi f C}}{R_o + \frac{1}{j \cdot 2\pi f C}} \times V_o$$

As a capacitor's capacitance increases, its impedance decreases, with the result that the effect of the voltage drop caused by the division of the voltage by the measuring instrument's output resistance becomes more pronounced. To ascertain the effects of voltage dependence, it is necessary to monitor the signal level applied to the DUT. Recently, impedance measuring instruments provide functionality for monitoring the measurement level[2]. This functionality eliminates the need to use an external device such as a multimeter to monitor the level.

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[2] As of November 2017, all LCR meters and impedance analyzers sold by Hioki provide this functionality.

(2) Current dependence

Measured values for inductors vary with the signal current. Increasing the signal current flowing to the inductor has the effect of decreasing the inductance value. Since exceeding the allowable current would destroy the inductor, it is necessary to exercise caution so that the impedance measuring instrument is not used improperly. Generally speaking, the effective inductance value for inductors decreases as the superposed DC bias current increases, as illustrated in Figure 4.

Most inductance measuring instruments define the measurement signal level in terms of the open voltage across the measurement terminals. Because the current value flowing to the DUT in this case varies with the output resistance of the impedance measuring instrument, the signal current may vary for different measuring instruments, even if the output voltage is set to the same value. To avoid this issue, it is optimal to utilize CC measurement mode, which keeps the current flowing to the DUT at a constant level.

The current I_{DUT} that flows to the DUT with a measurement frequency of f can be expressed by the following formula, where R_O indicates the output resistance; L, the DUT's inductance value; and V_O, the signal source voltage:

$$I_{DUT} = \frac{V_o}{R_o + j \cdot 2\pi f L}$$

Since inductors consist of a winding made of wire with a specific resistance value, they have DC resistance. Wound coils heat up due to the loss from the wire's resistance when current flows through them, and the heat causes the inductance value to vary. For DC currents, the heat derives entirely from this resistance, but for AC currents, heat from the wire's skin effect and magnetic material loss is added. These characteristics comprise the inductor's loss resistance. The loss resistance is related to the quality factor (or Q-value), which indicates the inductor's performance.

The Q-value indicates how low the inductor's loss resistance is, with larger Q-values indicating ideal inductors. The Q-value can be expressed by the following formula, where f indicates the measurement frequency; L, the DUT's inductance; and R, the inductor's loss resistance:

$$\mathrm{Q} = \frac{2\pi f L}{R}$$

Although dedicated Q-meters were used in the past, today the quantity is measured using impedance measuring instruments.

-3 Compensation

The measurement accuracy of impedance measuring instruments is defined at the tip of the coaxial connector. However, since DUTs of a variety of shapes cannot be connected directly to a coaxial connector, ordinarily DUTs are connected via a test fixture or cables. To accurately measure the impedance of the DUT, it is necessary to eliminate the effects of the fixture's residual impedance and the cables. Consequently, impedance measuring instruments are equipped with the following compensation functionality:

- Open and short compensation
- Load compensation
- Cable compensation

(1) Open and short compensation

Open and short compensation functionality eliminates errors caused by the test fixture's residual component.

Imagine a DUT and measuring instrument that comprise a test fixture equivalent circuit such as that depicted in Figure 5, where Z_s indicates the impedance in series with the DUT and Y_o indicates the admittance in parallel with the DUT.

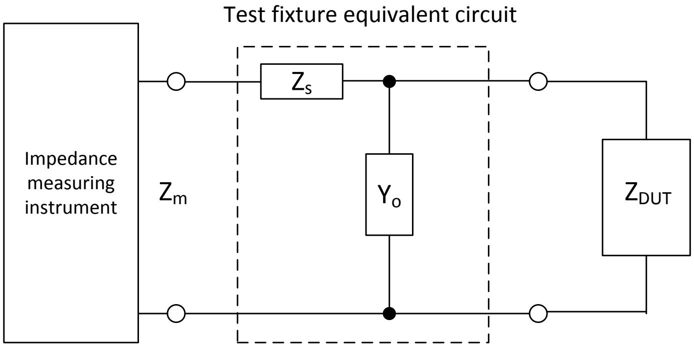

Figure 5. Test fixture equivalent circuit

The DUT's impedance true value Z_{DUT} can be expressed as follows, where Z_m indicates the impedance that is measured at the measuring instrument's measurement terminals:

$$Z_{DUT} = \frac{Z_m - Z_S}{1 - Y_o(Z_m - Z_s)} \quad \cdot\cdot\cdot \quad (1.3.1)$$

By performing open and short compensation, it is possible to correct Z_m when Z_{DUT} is open (=Z_{om}) and Z_m when Z_{DUT} is shorted (= Z_{sm}). Z_{om} and Z_{sm} can be calculated using the following formulas:

$$Z_{om} = Z_s + \frac{1}{Y_o} \quad \cdot\cdot\cdot \quad (1.3.2)$$

$$Z_{sm} = Z_s$$

Impedance measuring instruments calculate measured values using the following formula from the values obtained from Equations 1.3.1 and 1.3.2:

$$Z_{DUT} = \frac{(Z_{om} - Z_{sm})(Z_m - Z_{sm})}{Z_{om} - Z_m}$$

Note the following when performing open and short compensation:

Precautions when performing open compensation

- Perform open compensation after allowing the instrument to warm up.
- Perform open compensation with the same distance between measurement terminals as will be used during actual measurement.
- Exercise caution concerning the effects of noise as the process utilizes high-impedance measurement.
- If you encounter a compensation error due to the effects of noise, implement guarding.

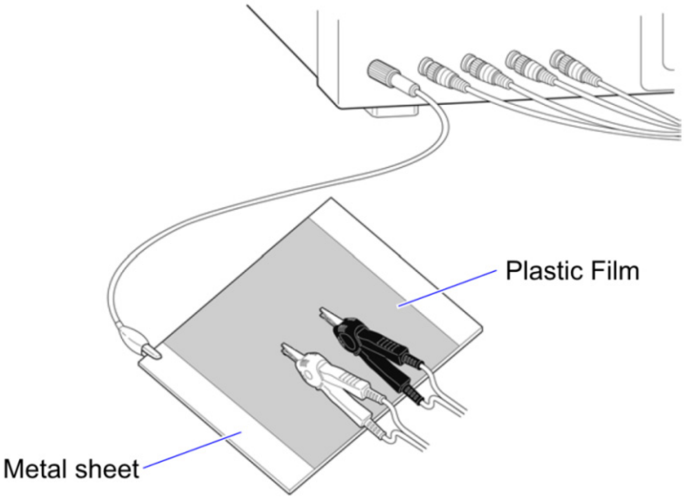

Figure 6. Example of guarding

Precautions when performing short compensation

- Perform short compensation after allowing the instrument to warm up.
- Connect the measurement terminals directly or use a shorting component.
- Use a shorting component with a low residual impedance.
- Route the cables in the same way as they will be routed during actual measurement.

In the following circumstances, repeat open and short compensation:

- If the fixture or cables change

  The residual impedance and residual admittance will change.
- If the impedance measuring instrument’s measurement conditions change

  A change in the measurement conditions may invalidate the compensation results.

Limits of open and short compensation

When the equivalent circuit for the fixture and cables between the impedance measuring instrument and the DUT is clearly more complex than the circuit shown in Figure 5, for example transmission lines or circuits combining multiple elements, it may not be possible to eliminate the effects of the fixture and cables, even when open and short correction are performed.

(2) Load compensation

When a complex circuit is connected between the DUT and the measuring instrument, making it impossible to eliminate the effects of the circuit even if open and short compensation are performed, load compensation can be effective as a method of aligning measured values and reference values. The load compensation procedure consists of measuring a component whose value is accurately understood and then calculating a compensation coefficient. Measured values can then be calculated by applying the compensation coefficient to observed values.

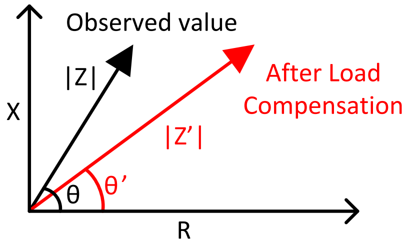

Figure 7. Illustration of load compensation

(3) Cable length compensation

Cable length compensation comprises functionality for correcting errors that arise from coaxial cables' transmission characteristics.

Extending the length of the cables between the measuring instrument and the DUT causes errors in the amplitude and phase of the signal applied to the DUT. This effect becomes more pronounced the higher the measurement frequency, and it can also introduce an error component into impedance measured values.

Hioki's impedance measuring instruments are adjusted prior to shipment from the factory based on the coaxial cable they use as described below. When extending the coaxial cables, use cables that satisfy the conditions listed below, and configure the cable length setting accordingly.

- Use coaxial cables with a characteristic impedance of 50 Ω (1.5D-2V, etc.).
- For the IM35xx series and 350x series, adjust the length of each cable so that its capacitance conforms to the following limits:

Instrument cable length setting of 1 m: 111 pF/cable

Instrument cable length setting of 2 m: 215 pF/cable

Instrument cable length setting of 4 m: 424 pF/cable

-4 Measurement terminal structure

When performing measurement with an impedance measuring instrument, it is necessary to establish contact with the DUT via probes or a fixture. Most impedance measuring instruments[3] have four measurement terminals, and the method of connecting the instrument to the DUT varies with the probe and fixture structure as well as the shape of the measurement target.

In order to measure impedance with a high degree of precision, it is important to choose the most appropriate method for connecting the DUT based on an understanding of potential sources of measured value variability and errors.

(1) Two-terminal connections

The two-terminal connection is the simplest connection type, as illustrated in Figure 8.

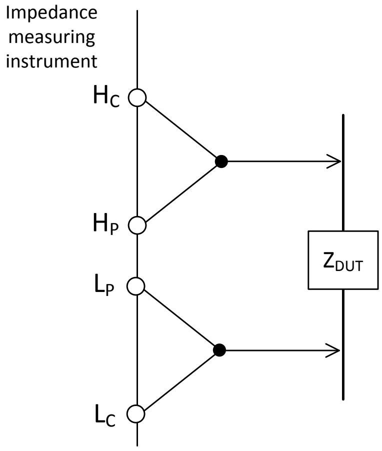

Figure 8.

Two-terminal connection

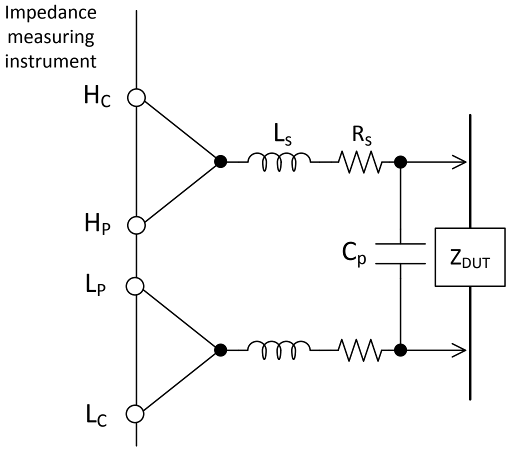

Figure 9.

Sources of error with two-terminal connections

In an actual two-terminal connection, the parasitic components listed in Figure 9 cause errors. Impedance as measured by impedance measuring instruments is the synthetic impedance of L_s, R_s, C_p, and Z_{DUT}. Consequently, two-terminal connections are used in measurement at frequencies of several kilohertz and less, where the setup is more resistant to the error sources illustrated in the figure, and where the impedance of the DUT ranges from 50 Ω to about 10 kΩ. For more information about the relationship between impedance values and error sources, see Table 1:

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[3] Of products that utilize the auto-balancing bridge measurement method. These products are equivalent to Hioki's IM35xx series and 35xx series.

Table 1. Sources of error in two-terminal connections and their effects

Error source		Effect
L_s	Parasitic inductance of cables and probes	Significant effect when measuring low impedance at a high frequency
R_s	Cable parasitic resistance and probe contact resistance	Effect if Z_{DUT} is not significantly greater than R_s
C_p	Parasitic capacitance between cables and probes	Significant effect when measuring high impedance at a high frequency

(2) Four-terminal connections

In a four-terminal connection such as the one illustrated in Figure 10, the impedance measuring instrument's current signal path and voltage signal path are independent. Since this circuit is resistant to the effects of contact resistance in the frequency band where the input impedance of the voltage detection circuit is high (measurement frequencies of 1 MHz and lower), this connection makes it possible to measure low impedance values. However, the parasitic capacitance that exists between the cables becomes a source of error during high-impedance measurement, as illustrated in Figure 11.

Four-terminal connections can be used when the DUT's impedance is within the range of 100 mΩ to about 10 kΩ.

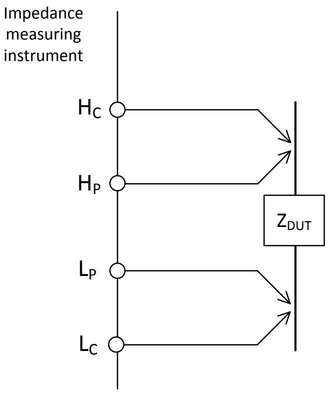

Figure 10.
A four-terminal connection

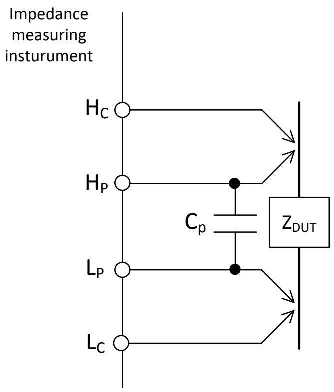

Figure 11. Source of error in a four-terminal connection

(3) Five-terminal connections

Due to the existence of parasitic capacitance between cables in a four-terminal connection, it is necessary to reduce the effects of this capacitance with shielding as illustrated in Figure 12, for example by using coaxial cables, particularly during high-impedance measurement. This type of connection is known as a 5-terminal connection.

Five-terminal connections can be used with DUTs whose impedance falls within the range of

100 mΩ to about 10 MΩ.

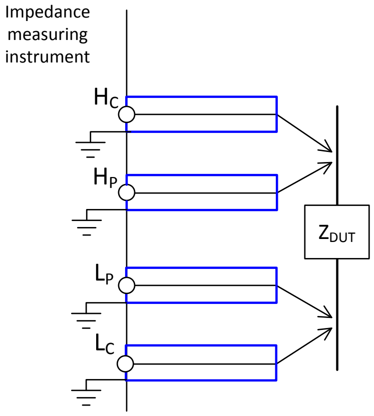

Figure 12. A five-terminal connection

(4) Four-terminal-pair connections

Even a five-terminal connection does not eliminate all sources of error. During low-impedance measurement, a large current flows to the DUT and cables as the measurement signal. As a result, inductive coupling between cables results in an error component.

When using a four-terminal-pair connection such as that illustrated in Figure 13, the current flowing to the DUT and the current flowing to the shielding are the same magnitude (but opposite direction). The magnetic flux created by the measurement signal is canceled out by the magnetic flux created by the current flowing to the shielding, and as a result inductive coupling between cables is prevented. A four-terminal-pair connection allows low impedance to be measured with a higher degree of precision than a five-terminal connection.

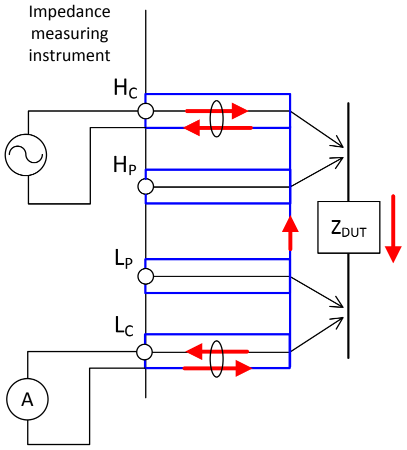

Figure 13. A four-terminal-pair connection

-5 Effects of contact resistance

Contact resistance is resistance that occurs between the impedance measuring instrument and the fixture, and between the fixture and the DUT. It arises due to a variety of factors, including electrode wear, probe wire breaks, and inadequate contact pressure. It's necessary to minimize contact resistance during impedance measurement because it gives rise to measurement errors.

Figure 14 illustrates the parts of a measurement circuit that are affected by contact resistance. In the illustration, R_{xx} indicates contact resistance, while C_{xx} indicates cable capacitance. The magnitude of the effect depends on the connection type (two-terminal measurement and four-terminal measurement).

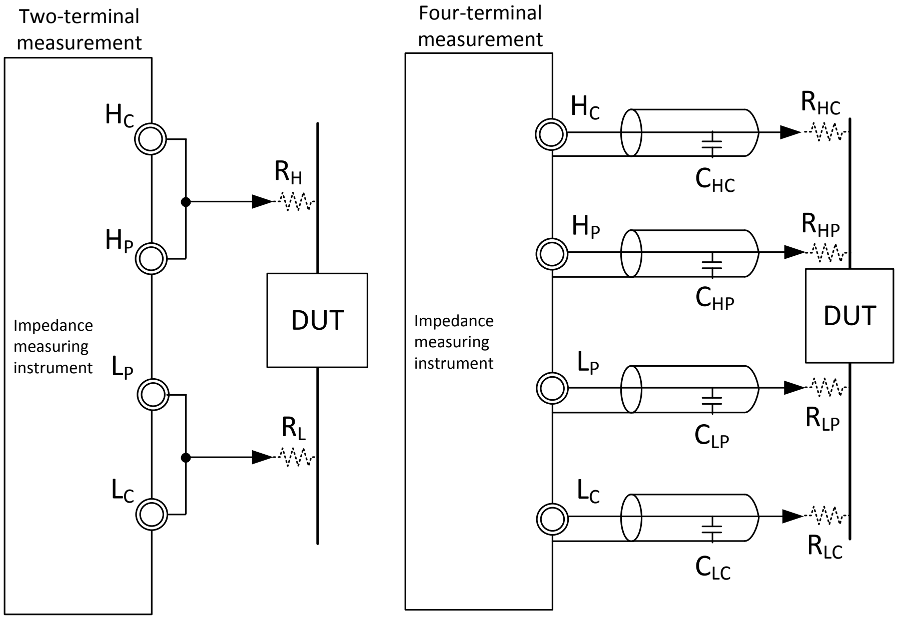

Figure 14. Locations affected by contact resistance by connection type

- In two-terminal measurement, the contact resistance R_H and R_L are in series with the DUT.
- In four-terminal measurement, the magnitude of the effect depends on the terminal at which the contact resistance exists.
- R_{HC} and R_{LC} lower the signal level applied to the DUT.
- R_{HP} results in an error in voltage detection since it forms a low-pass filter with C_{HP}.
- R_{HP} and R_{LP} result in an error in voltage detection since they degrade the voltage detection circuit's common mode rejection ratio (CMRR).
- Since the measurement current flows to R_{LC} and increases the L_P terminal voltage, an error will occur in voltage detection if the voltage detection circuit's CMRR is not sufficiently large.

(1) Example error when performing two-terminal measurement

R_s and D can be calculated as shown in the following formula, where R indicates the DUT's equivalent series resistance; C, its capacitance; and f, the measurement frequency.

$$R_S(\mathrm{ESR}) = (R)_{\mathrm{True\ value}} + (R_H + R_L)_{Error}$$

$$D = \frac{R}{X} = \frac{(R + R_H + R_L)}{\frac{1}{2\pi f C}} = (R \cdot 2\pi f \mathrm{C})_{\mathrm{True\ value}} + (R_H \cdot 2\pi f c + R_L \cdot 2\pi f C)_{\mathrm{Error}}$$

(2) Example error when performing four-terminal measurement

The error caused by R_{HP} and C_{HP} affects voltage detection and can be calculated as follows:

Measurement error $\frac{1}{\sqrt{1 + (2\pi f \cdot C_{HP} \cdot R_{HP})^2}} - 1$

Phase error $\tan^{-1}(-2\pi f \cdot C_{HP} \cdot R_{HP})$

(3) Contact check functionality

Some impedance measuring instruments provide contact check functionality. Such functionality detects the contact resistance, providing an effective way to reduce the testing issues it causes.

2 Precautions when fabricating your own measurement cables and other components

-1 Cables

This section provides considerations when fabricating your own cables.

(1) Selecting cables

- Use coaxial cables with a characteristic impedance of 50 Ω (1.5D-2V, etc.).
- For the IM35xx series and 350x series, adjust the length of each cable so that its capacitance conforms to the following limits[4]:
  Instrument cable length setting of 1 m: 111 pF/cable
  Instrument cable length setting of 2 m: 215 pF/cable
  Instrument cable length setting of 4 m: 424 pF/cable

(2) Method for fabricating noise-resistant cables

Observe the following considerations in order to make cables as resistant to external noise as possible:

- Use a four-terminal-pair structure like the one illustrated in Figure 15.
- Connect shielding as close as possible to the DUT, and minimize the amount of exposed core wire.
- Twist the L_C and H_C terminal cables so that it is more difficult for noise to enter the cable. Similarly, twist the L_P and H_P terminal cables.

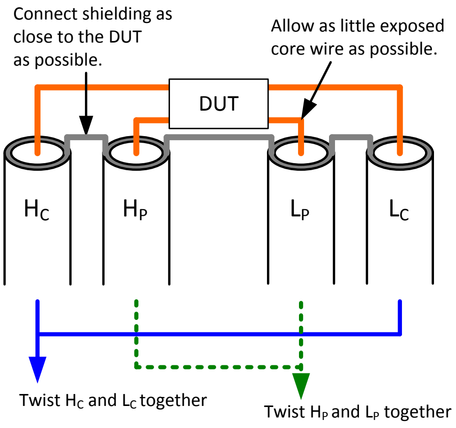

Figure 15. Method for fabricating noise-resistant cables

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[4] Hioki's impedance measuring instruments are adjusted prior to shipment from the factory based on cable length. When the capacitance between coaxial cables' core wires and shielding differs from the cables used in this adjustment process, measurement error occurs.

(3) Precautions when modifying the end of a cable to fabricate a two-terminal cable

- Perform open and short compensation at the probe tip.
- The cable will be susceptible to the effects of contact resistance (the cable is not suited to low-impedance measurement).

-2 Scanner fabrication

Fabricate the scanner so as to maintain the four-terminal pair structure. Figure 16 provides details.

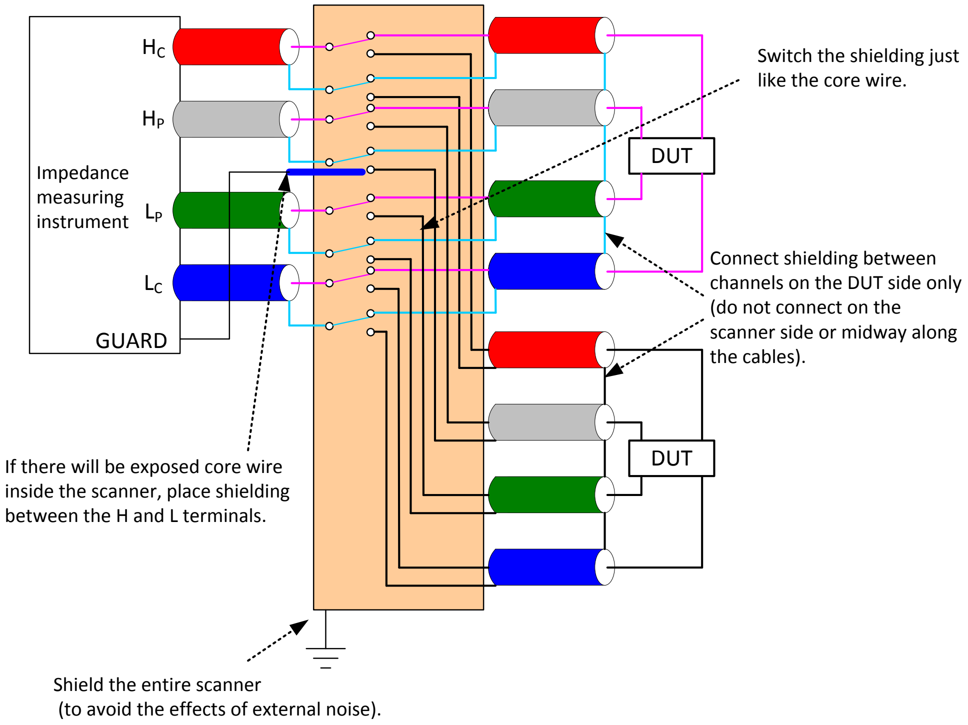

Figure 16. Precautions when fabricating a scanner

- Perform open and short compensation at the tip of the probe that is in contact with the DUT.
- Select switches for use in the scanner based on a consideration of the maximum current when the tips are shorted.
- When using the scanner in combination with an insulation tester or other instrument, switch to the impedance measuring instrument only after allowing the DUT to discharge adequately. Otherwise residual charge may damage the impedance measuring instrument (the residual charge protection function cannot withstand repeated application).

-3 DC bias voltage application circuits

This section describes how to fabricate DC bias voltage application circuits, which are used primarily to evaluate the voltage dependence of capacitors. Figure 17 illustrates a DC bias voltage application circuit.

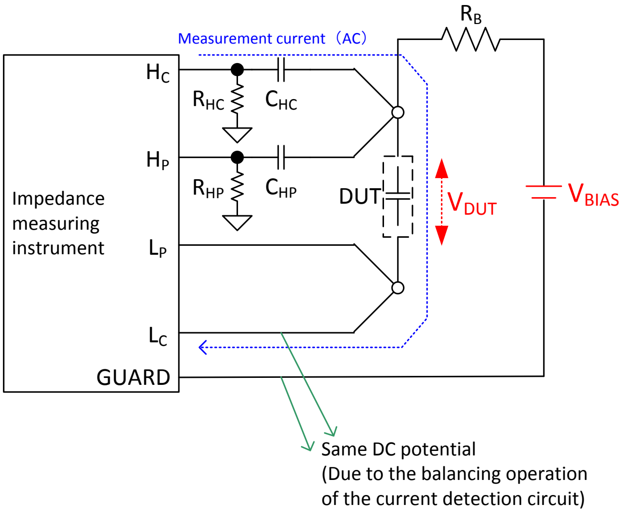

Figure 17. DC bias voltage application circuit

- Increase the output from the DC voltage source gradually after connecting the DUT to the measurement cables, probes, or fixture until the designated DC bias voltage is reached. When disconnecting the DUT, decrease the output of the DC voltage source gradually until the DC bias voltage being applied to the DUT reaches zero, and then disconnect the DUT.

(1) R_{HC}, C_{HC}, R_{HP}, and C_{HP}

- These components are used to keep the DC voltage from flowing to the impedance measuring instrument. Note that applying an external voltage to the impedance measuring instrument without installing an RC filter may damage the instrument[5].
- Select C_{HC} so that it produces a resistance of several ohms at the measurement frequency so that an adequate measurement current (AC) flows to the DUT. Verify that the capacitor's dielectric withstand voltage exceeds the DC bias voltage by a sufficient margin.
- Select R_{HC} so that it provides a resistance of about 10 kΩ to 100 kΩ in order to protect the impedance measuring instrument from the charge that accumulates in C_{HC}.

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[5] The residual charge protection function provided by instruments such as the IM3536 is designed to protect the impedance measuring instrument from the charge that accumulates in capacitors. It does not protect against a continuously applied voltage such as that from a DC source.

- Select R_{HP} so that it provides a resistance of about 10 kΩ to ensure that the voltage detection circuit has a high input impedance.
- Select C_{HP} so that the RC filter consisting of R_{HP} and C_{HP} has a cutoff frequency that is about 1/100 of the measurement signal frequency. The RC filter's cutoff frequency f_c can be calculated using the following formula:

  $$f_c = \frac{1}{2\pi CR} \ [\mathrm{Hz}]$$

  Verify that the capacitor's dielectric withstand voltage exceeds the DC bias voltage by a sufficient margin.
- It will take some time for the measured value to stabilize after the bias voltage is applied. The time t required for the measured value to stabilize can be calculated using the following formula, where C_{DUT} indicates the DUT's capacitance:

  $$t \ = \ 5 \times (R_* \cdot C_* + R_B \cdot C_{DUT}) \ \ [\mathrm{s}]$$

  $R_* \cdot C_*$: Choose the largest of $R_B \cdot C_{HC}$, and $R_{HP} \cdot C_{HP}$.

(2) Selecting R_B

Select R_B so that it provides a resistance that is about 10 times greater than the output resistance[6] that is built into the impedance measuring instrument. In addition, R_B must be sufficiently less than the DUT's DC resistance since V_{BIAS} is divided by the DUT's DC resistance and R_B[7].

R_B also serves as the current-limiting resistor for uncharged capacitors. Select it so that there is more than enough resistance for the rated power relative to the DUT's power consumption during charging. (A maximum current of V_{BIAS}/R_B will flow while the DUT and the C_{HC} and C_{HP} capacitors are charging.)。

(3) Example design

As an example, the DC bias voltage application circuit should be designed to satisfy the following conditions.

Table 1. Example DC bias voltage circuit design (conditions)

DUT	1.0 µF
Measurement frequency	1 kHz
DC bias voltage	10 V
Impedance measuring instrument output resistance	100 Ω

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[6] Check the specifications of the impedance measuring instrument.

[7] The L_C terminal and guard terminal will be at the same DC potential. This is due to the balancing operation of the current detection circuit.

i. Determine C_{HC}. Use a C_{HC} value of 47 µF so that the impedance value at 1 kHz is several ohms. The impedance value that corresponds to 47 µF at 1 kHz is approximately 3.39 Ω. Since the DC bias voltage is 10 V, select a component that can withstand at least 25 V.

ii. Use an R_{HC} value of 10 kΩ.

iii. Use an R_{HP} value of 10 kΩ.

iv. Determine C_{HP}. Using 1/100 of the measurement frequency of 1 kHz, or 10 Hz, as the RC filter's cutoff frequency results in a C_{HP} value of approximately 1.6 µF. Here, we use a C_{HP} value of 2.2 µF, which is a component value that is readily available. The cutoff frequency is approximately 7.23 Hz. Since the DC bias voltage is 10 V, select a component that can withstand at least 25 V.

v. Determine R_B. Use a value of 1 kΩ, which is 10 times the impedance measuring instrument's output resistance.

vi. Check the voltage division of V_{BIAS} that occurs due to R_B. A typical capacitor has an insulation resistance more than several hundred megohms. The selected value of 1 kΩ should be sufficiently small relative to the capacitor's insulation resistance, so it can be assumed that V_{DUT} is approximately equal to V_{BIAS}.

vii. Ascertain the rated power required by R_B. The maximum[8] consumed power is given by the following formula:

$$P = \frac{\left(V_{BIAS}\right)^2}{R_B} = \frac{10^2}{1 \times 10^3} = 100\ \mathrm{mW}$$

Leave some margin by selecting a component rated for at least 250 mW.[9]

Consequently, the following components can be selected:

---

[8] The DC current calculated in the formula will flow until the capacitor is fully charged. It will not flow continuously.

[9] Check for heating due to resistance and other effects during actual measurement.

Table 2. Example design of a DC bias voltage circuit (selected components)

Parameter	Selected component
C_{HC}	47 µF (dielectric withstand voltage of 25 V or greater)
R_{HC}	10 kΩ
C_{HP}	2.2 µF (dielectric withstand voltage of 25 V or greater)
R_{HP}	10kΩ
R_B	1 kΩ (rated power of 250 mW or greater)

It will take some time for the measured value to stabilize after the DC bias voltage is applied. For the above example design, the required stabilization time t can be expressed using the following formula:

$$t \ = \ 5 \times \{(1 \times 10^3) \cdot (47 \times 10^{-6}) + (1 \times 10^3) \cdot (0.1 \times 10^{-6})\} \approx 0.24\ \mathrm{s}$$

-4 DC bias current application circuits

This section describes how to fabricate DC bias current application circuits, which are used in primarily to evaluate the current dependence of capacitors. Figure 18 illustrates a DC bias current application circuit.

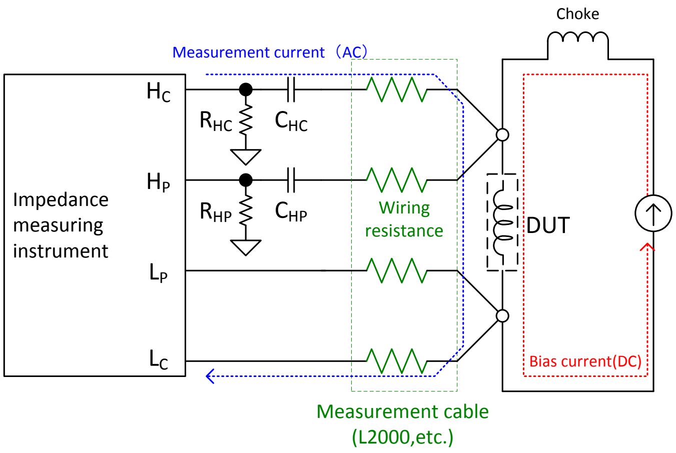

Figure 18. DC bias current application circuit

- Increase the output from the DC current source gradually after connecting the DUT to the measurement cables, probes, or fixture until the designated DC bias current is reached. When disconnecting the DUT, decrease the output of the DC current source gradually until the DC bias voltage being applied to the DUT reaches zero, and then disconnect the DUT.
- Exercise caution concerning polarity when connecting measurement cables, probes, the

fixture, DUT, and DC current source.

- Use a DC current source that is isolated from ground. Accurate impedance measurement is not possible when using a grounded DC current source.

(1) R_{HC}, C_{HC}, R_{HP}, and C_{HP}

- These components are used to keep the DC current from flowing to the impedance measuring instrument. Note that applying an external current to the impedance measuring instrument without installing an RC filter may damage the instrument.
- Select C_{HC} so that it produces a resistance of several ohms at the measurement frequency so that an adequate measurement current flows to the DUT. Exercise care concerning the capacitor's withstand voltage.

See also: -3(3) , "Example design"

- Select R_{HC} so that it provides a resistance of about 10 kΩ to 100 kΩ in order to protect the impedance measuring instrument from the charge that accumulates in C_{HC}.
- Select R_{HP} so that it provides a resistance of about 10 kΩ to ensure that the voltage detection circuit has a high input impedance.
- Select C_{HP} so that the RC filter consisting of R_{HP} and C_{HP} has a cutoff frequency that is about 1/100 of the measurement signal frequency.

See also: -3(3) , "Example design"

- It will take some time for the measured value to stabilize after the bias voltage is applied. The time t required for the measured value to stabilize can be calculated using the following formula:

$$t = 5 \times (R_{HP} \cdot C_{HP}) \ [\mathrm{s}]$$

  In addition to the above value of t, note that it will also take some time for the output current of the DC current source being used to reach the set value.

(2) Chokes

- It is synthetic impedance, illustrated in Figure 19, that is measured. Ensure that the choke's impedance value is sufficiently larger than that of the DUT so that the circuit is less susceptible to the effects of the impedance of the choke plus that of the DC current source.

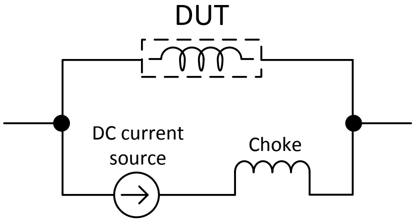

Figure 19. Synthetic impedance of DC bias application circuit and DUT

However, even if the inductance value is larger than that of the DUT, the current resistance will dominate at low frequencies, causing measurement error to increase.

- Choose a choke whose current rating is greater than or equal to the DC bias current.
- Choose a choke whose self-resonant frequency exceeds the measurement signal by a sufficient margin.

(3) Precautions concerning connection types

- Hioki's Four-terminal Probe L2000 has a current rating of 1 A_{peak}. If the DC bias current will exceed 1 A, use a connection type such that the bias current will not flow.

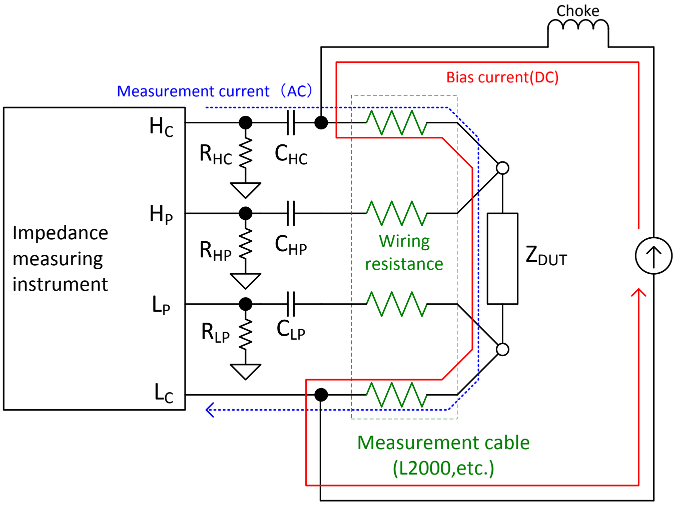

Figure 20. Connection that is susceptible to the effects of wiring resistance

In a connection such as that illustrated in Figure 20,

- There is the risk that the L2000 cables will overheat and sustain damage due to the bias current.
- The risk exists that a DC voltage will occur at the L_P terminal when the bias current flows to the wiring resistance, causing the internal protection circuit to operate and increasing measurement error. For connections that are susceptible to the effects of wiring resistance, add an RC filter to the L_P terminal as well, as shown in Figure 20.

3 FAQ

This section provides answers to common questions.

-1 How should I choose the measurement frequency?

(1) When you wish to view a component's frequency characteristics

When you wish to verify the characteristics of a particular component at a certain frequency, choose that frequency and measure the component. For example, you could use this approach to view the high-frequency characteristics of a capacitor that you are using as a bias capacitor.

(2) When you wish to verify that a component is functioning properly

Measure the component at the measurement frequency defined by the manufacturer. For example, capacitance values for electrolytic capacitors and other components are defined at 120 Hz. Since component characteristics vary with the measurement frequency, the values you obtain may diverge from the nominal values if you measure the component at a high frequency.

-2 How should I choose the measurement signal level?

(1) When you wish to view a component's level dependence

When you wish to check the characteristics of a component you are using at a given signal level, measure the component after setting the signal level to either CV mode or CC mode. For example, the capacitance of high-dielectric-constant laminated ceramic capacitors varies with the signal level and DC bias voltage due to the components' voltage dependence. In addition, the components' inductance values vary with the signal level and DC bias current because the core material in their inductors exhibits current dependence.

See also: 1 -2, "Measuring level-dependent elements"

(2) When you wish to verify that a component is functioning properly

Component characteristics vary with the measurement signal level. Measure the component at the signal level defined by the manufacturer. If a different signal level is used, measured values may diverge significantly from the inductance value error range defined by the manufacturer.

-3 How should I choose the measurement range?

(1) Auto range

Auto range functionality is useful when you wish to measure a component whose impedance is unknown. However, measurement times will be longer since it takes time for the instrument to switch to the appropriate mode during auto range operation.

To measure the frequency characteristics of a capacitor or inductor, measure the component using auto range mode since the DUT's impedance value will vary with the measurement frequency.

(2) Hold range

Measurement can be performed at high speed without switching between ranges by fixing the instrument to the appropriate range. The guaranteed accuracy range for each measurement range is defined separately for individual impedance measuring instruments, so please see the user manual for the instrument you are using. Additionally, measurement ranges are defined in terms of impedance values, not capacitance (C) or inductance (L) values. When measuring a capacitor or inductor, determine the range based on the component's impedance (Z) value.

-4 Please explain measurement speed and averaging.

The measurement time (integration time) varies depending on the measurement speed setting. Slower measurement speeds result in longer measurement times, but as a result measured values stabilize and measurement precision improves. The averaging function provides similar benefits by averaging measured values the set number of times.

-5 How should I choose between a series equivalent circuit and parallel equivalent circuit?

Since the impedance measuring instrument is unable to determine the measurement target's circuit mode, it is necessary to select the correct equivalent circuit mode in order to reduce error. Generally speaking, series equivalent circuit mode is used when measuring low-impedance elements (approximately 100 Ω or less) such as high-capacitance capacitors and low-impedance components, while parallel equivalent circuit mode is used when measuring high-impedance elements (approximately 10 kΩ or greater) such as low-capacitance capacitors and high-impedance components. If you need to measure a component whose equivalent circuit mode is unknown, for example a component with an impedance of 100 Ω to 10 kΩ, check with the component manufacturer.

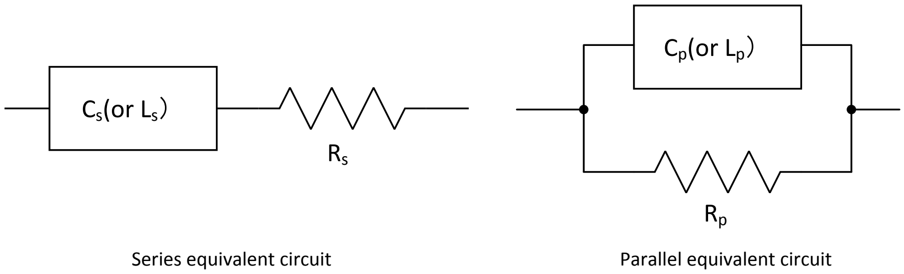

Figure 21. Series equivalent circuit and parallel equivalent circuit

-6 How does the measurement parameter R_{DC} differ from R_s and R_p?

R_{DC} is the DC resistance that is measured by applying a DC signal. R_s and R_p are the real number components of the AC impedance, expressed as $R_s = Z \times \cos\theta,\ R_p = \frac{1}{Y\cos(-\theta)}$, and as such they differ from the R_{DC} value. For example, an inductor loss includes copper loss and core loss, which are expressed as R_s and R_p, respectively. The R_s value denotes loss caused by wiring resistance and the skin effect, while the R_p value denotes loss such as hysteresis loss and eddy-current loss. Both differ from the R_{DC} value.

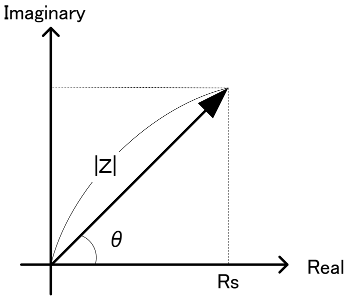

Figure 22. Relationship between impedance and R_s on a complex plane

-7 Is it possible to measure a grounded DUT?

Impedance measuring instruments cannot measure a grounded DUT because the current flowing to the DUT would escape to ground, increasing measurement error. In addition, the measuring instrument itself cannot be used without being grounded due to the danger of electric shock caused by the leakage current from the instrument's power supply.

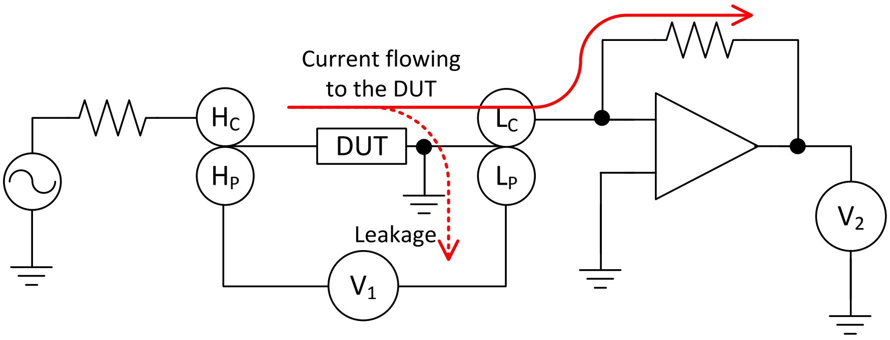

Figure 23. Current path for a grounded DUT

-8 Please explain how to measure the capacitance across a diode’s terminals.

Diodes have polarity. When an AC current is applied to a diode in the forward direction, the diode turns on, and when the current is applied in the reverse direction, the diode turns off. Consequently, distortion in the AC signal makes it impossible to accurately measure the capacitance across the terminals. Use the DC bias voltage application function to ensure that the signal is continuously applied in the reverse direction to allow accurate measurement. Under those conditions, the diode will remain in the off state, allowing measurement of the capacitance across its terminals.

Products that provide DC bias voltage application functionality include the IM3533 (-01), IM3536, IM3570, and IM3590. The external DC Bias Unit 9268 (-10) plays a useful role when combined with those and other impedance measuring instruments.

Without DC bias voltage application

With DC bias voltage application

Figure 24. Diode measurement using the DC bias function

-9 Please explain how to measure the characteristic impedance of a coaxial cable.

The characteristic impedance Z is calculated using the formula $Z = \sqrt{Z_o \times Z_s}$. Z_o indicates the impedance when the coaxial cable terminal is left open, while Z_s indicates the impedance when the terminal is shorted. To allow stable measurement, the cable should be connected to the impedance measuring instrument by connecting the outer conductor to the H_C and H_P terminals and the inner conductor to the L_C and L_P terminals, as shown in Figure 25. This connection type reduces the effects of noise, to which the impedance measuring instrument’s L_C terminal is prone, by shielding the inner conductor with the outer conductor.

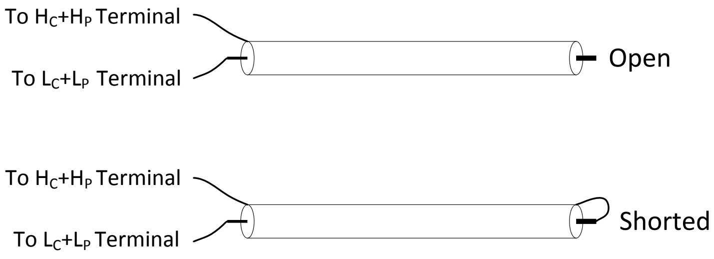

Figure 25. Measuring the impedance of a coaxial cable

-10 Please explain how to calculate the accuracy of an impedance measuring instrument.

The accuracy of impedance measuring instruments are defined in terms of impedance Z and phase difference θ. The accuracy of other measurement parameters is also calculated based on these Z and θ accuracy values. For example, an inductor's inductance value L_s can be calculated as $L_S = \frac{Z \times \sin\theta}{2\pi f}$ (where f indicates the frequency). By entering possible values for Z and θ as calculated from the accuracy of Z and θ into this formula, it is possible to calculate the possible values (accuracy) of L_s.

For more information about how to calculate accuracy, please see your impedance measuring instrument's user manual. In addition, you can automatically calculate accuracy by downloading the LCR Sample Application from Hioki's website.

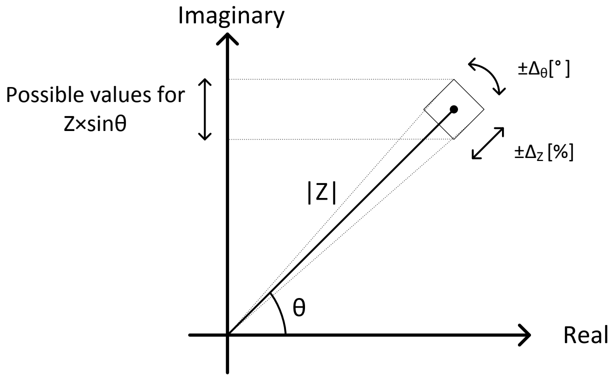

Figure 26. Calculating the accuracy of an impedance measuring instrument

-11 I'm unable to obtain a measured value that aligns with the corresponding nominal value.

Since measured values may vary when different measurement conditions are used, it is necessary to perform measurement using the same measurement conditions (measurement frequency and signal level) as the component manufacturer. For example, laminated ceramic capacitors with high dielectric constants exhibit a high degree of voltage dependency. In addition, the magnetic permeability of the core material in an inductor with core material exhibits current dependence, causing inductance values to vary with the measurement current. JIS C5101 defines measurement frequencies and measurement signal levels for capacitors. Check with the manufacturer for inductors as there is no equivalent standard.

-12 I get different measured values from different impedance measuring instruments, even when I configure them with the same settings.

The DUT's impedance value may be exhibiting variability due to differences in the measurement signal level that are caused by differences in the impedance measuring instruments' output resistance (10 Ω, 100 Ω, etc.). This is because the current that flows to the DUT and the voltage that is applied to the DUT will vary if the output resistance varies, even if the instruments are set to the same AC signal level. Check the specifications of the impedance measuring instrument you are using to confirm its output resistance.

-13 Are AC impedance and DC resistance measured at the same time?

The IM35xx can measure both AC impedance and DC resistance. To measure DC resistance, add R_{DC} as a display parameter. The instrument will measure AC impedance first and then DC resistance.

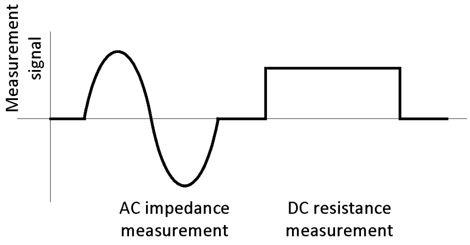

Figure 27. Time-axis relationship of AC measurement and DC measurement

-14 The measured values I get in the four-terminal open state exhibit variability.

Measured values exhibit variability, and the instrument may be unable to determine the measurement range, when its four measurement terminals are in the open state. This does not indicate a problem with the impedance measuring instrument, because it is calculating impedance values when the voltage detection signal and current detection signal levels are low or unstable. Measured values will stabilize if you connect a test fixture or measurement probes to the instrument such that the H_C and H_P terminals and the L_C and L_P terminals are shorted.

-15 Measured values when measuring low impedance exhibit an excessive amount of variability.

Test fixtures and measurement probes are available with a two-terminal design. Since two-terminal probes are susceptible to the effects of contact resistance, they may prevent measured values from stabilizing if the DUT has a low impedance. This is because the contact resistance is unstable and varies with factors including contact pressure.

-16 Measured values for DC resistance exhibit variability.

The IM35xx series provides functionality[10] [11] for reducing power supply noise by synchronizing the integration time with the power supply frequency's period for DC resistance measurement. Set the power supply frequency (50 or 60 Hz) prior to measurement. This functionality is particularly effective during high-impedance measurement.

-17 I'm seeing strange measured values for an inductor's DC resistance.

When an impedance measuring instrument performs DC resistance measurement, it cancels out its own internal offset voltage to reduce measurement error by turning the generated voltage on and off. (This is accomplished by the DC adjustment function). When the voltage applied to the inductor switches, transient phenomena are caused by the output resistance and the inductor's equivalent series resistance and inductance. Since such phenomena preclude accurate measurement, be sure to set a delay time for DC measurement that is long enough to ensure that these phenomena are not included in measurement. The name given to this delay time and the available timing methods vary by instrument model, so please consult your instrument's user manual. If you are unsure of the appropriate delay time, try measuring the component with as long a delay time as possible and then gradually shorten the time while verifying that there is no change in the measured values.

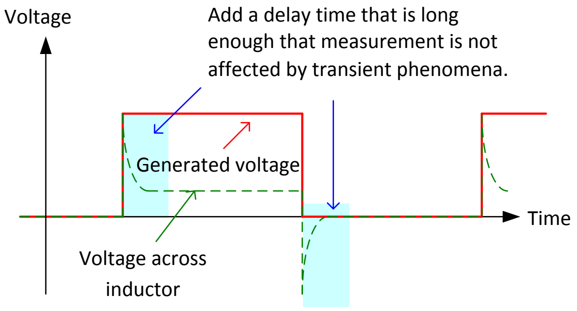

Figure 28. Transient phenomena during inductor measurement

-18 I get different inductance values when measuring different locations on an inductor.

Nearby conductors will affect the inductance value and Q-value when measuring an inductor. This is because the leakage flux from the inductor causes an eddy current in the conductor, and the resulting flux cancels out the original flux. Measure inductors as far from conductors as possible. Open-magnetic-circuit type inductors are more prone to the effects of nearby conductors than closed-magnetic-circuit type inductors.

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[10] The IM3570 does not provide this functionality.

[11] This function is not available when using the IM3536's FAST measurement speed.

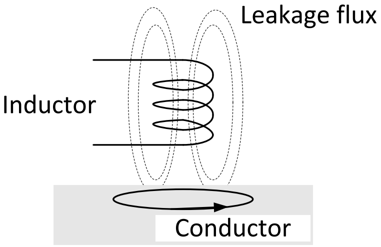


Figure 29. Effects of a coil's leakage flux

-19 Measured values exhibit an error component when using multiple instruments.

When multiple DUTs are positioned close to each other and measured using multiple impedance measuring instruments, measurement error (in the form of shifting values or increased variability) may result from interference among the instruments. The extent of these effects varies with factors such as distance, measurement frequency, and measurement speed. The following three measures are effective in reducing the effects of interference:

(1) Separate each DUT/measurement cable pair. Shield the DUT.

Interference can be caused by capacitive coupling resulting from the voltage of nearby DUTs as well as electromagnetic coupling resulting from current flowing to the DUTs. Separate the DUTs to reduce coupling. In addition, if capacitive coupling is to blame, it is effective to place shielding between the DUTs. If electromagnetic coupling is to blame, reduce the effects of flux by twisting together the H_C and L_C terminals of the measurement cables to cancel flux and by twisting together the H_P and L_P terminals to make the loop smaller.

(2) Change the timing at which you're making measurements.

The effects of interference can be reduced by staggering the timing at which DUTs are measured rather than measuring multiple DUTs simultaneously (although this approach results in longer measurement times). Use the trigger synchronization function to turn off the output signal for impedance measuring instruments that are not performing measurement.

(3) Change the measurement frequencies.

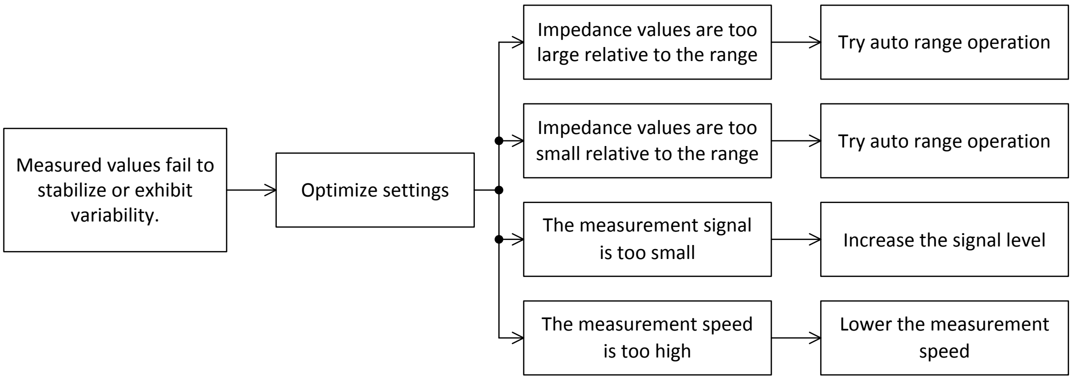
Using the same measurement frequency for multiple impedance measuring instruments increases the likelihood of interference. You can reduce the effects of interference by using different measurement frequencies. This is because impedance measuring instruments use internal synchronous detection calculations to extract only the measurement frequency for measurement. The effectiveness of this approach varies with the measurement frequency, measurement speed, and difference in frequencies.

4 Troubleshooting

Refer to the charts provided below if you encounter difficulty during measurement, for example because measured values fail to stabilize or conform to expectations.

-1 Measured value instability and variability

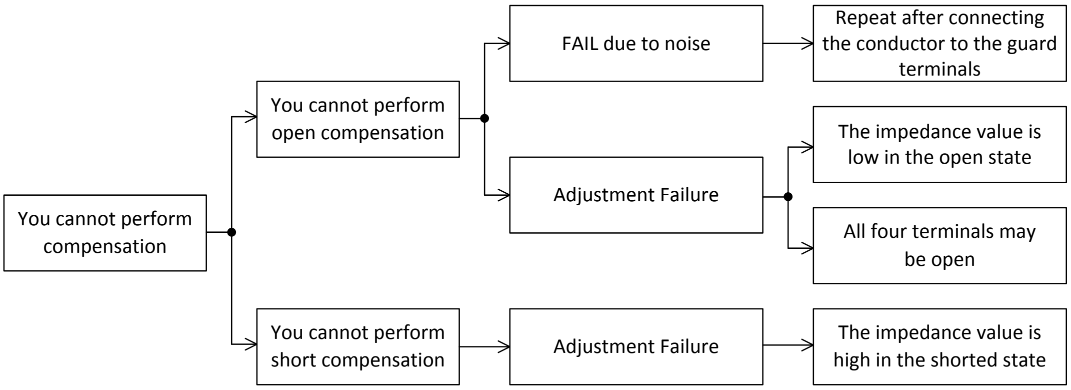
You may be able to address the failure of measured values to stabilize by optimizing the instrument's settings.



See also: 1 -1, "Optimizing measurement conditions"

-2 Inability to perform open or short compensation

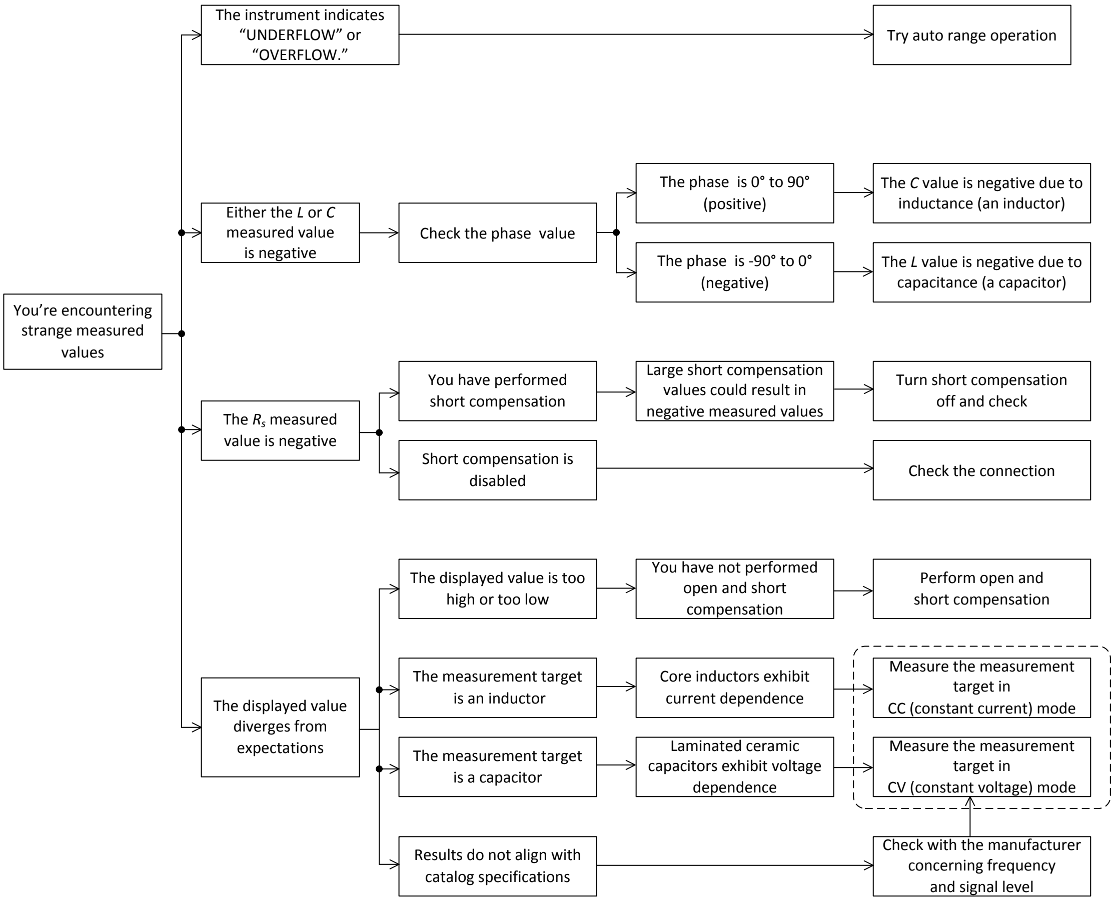
To allow measurement at a high level of precision, it is necessary to perform open and short compensation appropriately prior to measurement. Refer to the charts provided below if you are unable to complete the compensation process.



See also: 1 -3, "Compensation"

-3 Strange measured values

If you obtain measured values that differ from the expected results, you may be encountering an issue with not only the instrument's settings, but also the measurement target's characteristics.



See also: 1 -2, "Measuring level-dependent elements"

Revision history

Edition	Date of publication	Revision history
01	April 2018	Publication of initial edition