Guide on RLC/EIS Meter Low Impedance Measurements

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Abstract

Following document is practice guide for measurement of low impedances using RLC bridge and EIS spectrum meters. In its first part it covers general problems related to the measurement of low impedances. It shows various impedance standard types, proper connections to the bridge/EIS meter and corrections that can be applied to improve uncertainty of measurement. This section of the guide has no ambition to cover entire impedance measurement problematic. It just focuses to problems that are typical for low impedances. The general problem of impedance measurement was already sufficiently described in details in guide "Impedance Measurement Handbook" [6]. Authors of this guide strongly encourages readers of this guide to read the aforementioned Keysight Handbook before continuing with following chapters.

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Contents

1 Low impedance measurement

Electrical impedance measurement is, in principle, an extension of DC resistance measurement by using alternating current (AC) instead of direct current (DC). The use of AC current conveniently eliminates one problem common for many DC measurements, the thermoelectric effects. As the polarity of the excitation current and measured voltage drop alternates, the offsets caused by the thermal voltages are subtracted for each period of the AC signal. On the other hand, the use of AC current brings a lot of another complications which makes AC impedance metrology quite challenging. First and fundamental difference is the DC resistance R_{DC} (real number) becomes a complex impedance $\hat{Z}$, which has its magnitude $|Z|$ and phase angle ϕ (polar form) or real and imaginary components R_{S} and X_{S} (Cartesian form):

$$\hat{Z}_{\mathrm{X}} = \frac{\hat{U}_{\mathrm{X}}}{\hat{I}_{\mathrm{X}}} = R_{\mathrm{S}} + jX_{\mathrm{S}} = |Z| \cdot e^{j\phi}, \tag{1}$$

where $\hat{U}_{\mathrm{X}}$ is measured voltage drop and $\hat{I}_{\mathrm{X}}$ is current via the impedance $\hat{Z}$ according Fig. 1. The common problem with the DC measurement is measurement offset due to series impedance (resistance) of terminals. The left circuit in Fig. 1 shows simple two terminal connection (2T), where the measured voltage drop $\hat{U}_{\mathrm{X}}$ is increased by the voltage drops on the terminals impedances $\hat{Z}_{\mathrm{CH}}$ and $\hat{Z}_{\mathrm{CL}}$. Such connection is sufficient only for high impedances, where the terminals have negligible impedance compared to the measured impedance $\hat{Z}$. For low impedances, the four terminal connection (4T) is used, same as in case of DC resistance metering. If the sensing current via the series impedances $\hat{Z}_{\mathrm{PH}}$ and $\hat{Z}_{\mathrm{PL}}$ of potential terminals is negligible, the effect of the current terminals impedance is suppressed.

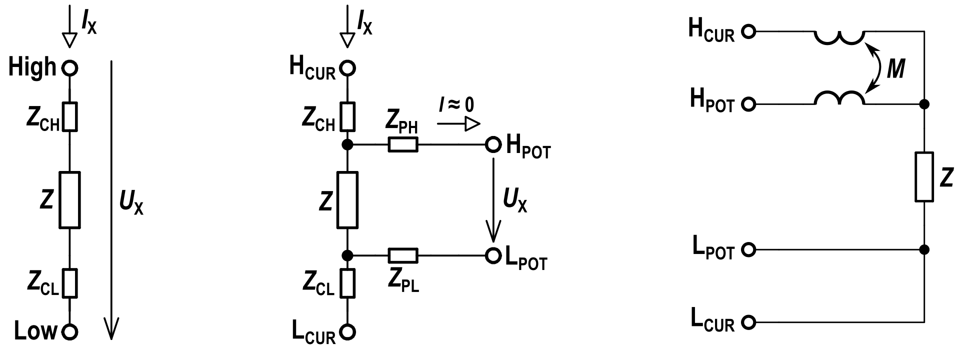


Figure 1: Basic types of DC resistance and impedance measurements. Left: 2-terminal (2T), Middle: 4-terminal connection (4T), Right: Mutual coupling problem for 4T measurements.

However, 4T measurement is the point where DC resistance and impedance metrology starts to diverge. Whereas for DC resistance the only condition for accurate measurement is low (ideally zero) current leakage via the potential terminals $\mathrm{H_{POT}}$-$\mathrm{L_{POT}}$, in case of impedance it is also necessary to take into account mutual couplings (mutual inductance) between the particular terminals, namely between current and potential ones as is illustrated in Fig. 1 on the right.

The mutual inductance M between the current lead $\mathrm{H_{CUR}}$ and potential lead $\mathrm{H_{POT}}$ will result in apparent series reactance of the 4T measurement:

$$X_{\mathrm{M}} = \omega \cdot M, \tag{2}$$

where ω is angular frequency of the measurement. When measuring pure resistance R, the mutual inductance will result in apparent shift in measured time constant τ of the impedance:

$$\Delta\tau = \frac{M}{R}. \tag{3}$$

Alternatively, angular error of the impedance $\hat{Z}$ measurement can be expressed:

$$\Delta\phi = \frac{M}{R} \cdot \omega. \tag{4}$$

Assuming example of measured impedance of 1 Ω (pure resistive), frequency of 1 kHz and mutual coupling just 20 nH, which is very optimistic estimate of non-coaxial leads connection, the apparent reactance will be 125 µΩ and thus angular error of measurement will be roughly 7°.

Apparently, even small coupling can cause significant errors of measurement. Although this effect can be suppressed by performing so called SHORT correction, the geometrical repeatability of the leads connection to the measured impedance will be limiting factor of measurement accuracy. Therefore, in impedance metrology, classical 4T measurement of low impedances is not preferred. Instead, the four terminal-pair (4TP) connection was introduced. The principle is shown in Fig. 2. In 4TP connection, the

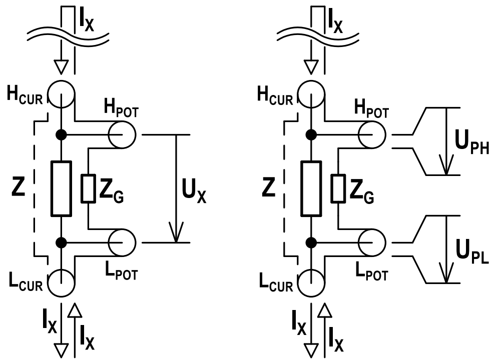


Figure 2: Four terminal (left) vs. four terminal-pair connection (right) measurement of 4TP impedance standard.

measurement current $\hat{I}_{\mathrm{X}}$ is sent through the impedance standard $\hat{Z}_{\mathrm{X}}$ and the current then returns back to the source through to coaxial shield as shown in the Fig. 2. The shield is usually grounded to the fifth terminal of the bridge, which is measurement ground or guard, hence such connection is sometimes called five-terminal (5T). This arrangement partially reduces effective inductance of the standard due to mutual coupling between the shield and internal impedance element and connection, but mainly, if properly mechanically designed, it reduces magnetic radiation of the current cables. The current via the impedance $\hat{Z}_{\mathrm{X}}$ is opposite to the current via the shield, so their magnetic fields subtract and mostly eliminate each other. Therefore, even if there is mutual coupling between the potential and current cables, the effect is greatly reduced. This is of course truth only for the coupling between the cables, but internal structure of the standard has finite dimensions, so residual magnetic radiation will be always present, but still reduced.

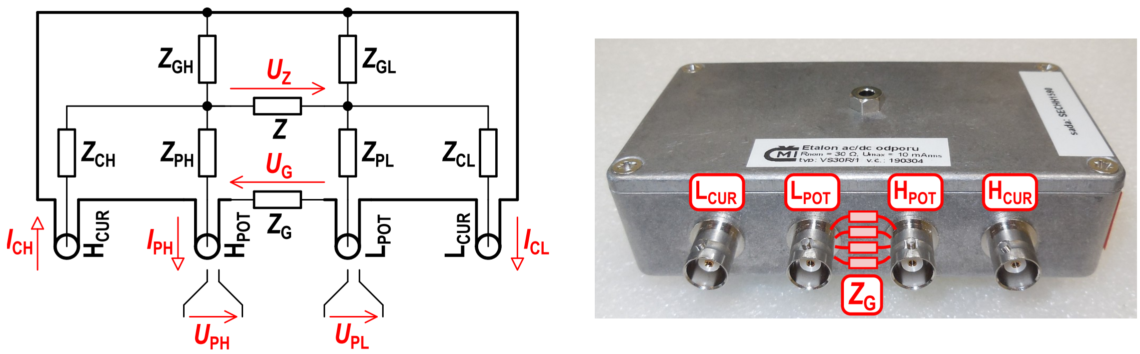


Figure 3: Illustration of shield impedance of 4TP standard.

However, another problem arises from the nature of 4TP standard. True 4TP measurement of impedance is defined as follows:

$$\hat{Z}_{\mathrm{EF}} = \frac{\hat{U}_{\mathrm{PH}} - \hat{U}_{\mathrm{PL}}}{I_{\mathrm{X}}}, \tag{5}$$

where $\hat{U}_{\mathrm{PH}}$ and $\hat{U}_{\mathrm{PL}}$ are port voltages shown in Fig. 2 on the right and $\hat{I}_{\mathrm{X}}$ is current via the standard. Therefore, if there is impedance of the standard's shield $\hat{Z}_{\mathrm{G}}$ between the ports $\mathrm{H_{POT}}$ and $\mathrm{L_{POT}}$ as shown in Fig. 3, it will inevitably become part of the measured effective impedance of the standard:

$$\hat{Z}_{\mathrm{EF}} = \frac{\hat{U}_{\mathrm{PH}} - \hat{U}_{\mathrm{PL}}}{I_{\mathrm{X}}} = \hat{Z} + \hat{Z}_{\mathrm{G}}. \tag{6}$$

This shield impedance is present for all the standards having e.g. four BNC ports placed inline in typical 19 mm spacing if they are directly electrically connected to the conductive base plate of the standard's box. Even bulky copper base would have some 100 µΩ of resistance, so 10% relative difference between 4T and 4TP measurement as shown in Fig.2 will appear for 1 mΩ nominal resistance!

Practical example of the ground impedance effect is shown in Fig. 4. The DC resistance (black cross) was measured in 4T definition (ignoring the shield impedance $\hat{Z}_{\mathrm{G}}$). The measured shield impedance of the standard was $\hat{Z}_{\mathrm{G}} \approx 230$ µΩ. The red trace shows 4TP reference measurement of series resistance R_{S} performed by digital sampling bridge that has fully balanced currents in all its coaxial ports, i.e. it measured according to 4TP definition in formula 6. As expected, the R_{S} exhibits fixed offset of roughly +230 µΩ above the DC value, as the $\hat{Z}_{\mathrm{G}}$ became part of the measured impedance. However, when the same standard was measured by common RLC bridge Keysight E4980A (blue trace), the results showed offset compared to the reference 4TP measurement (red trace) despite E4980A errors were corrected by another 100 mΩ standard. This effect is caused by the poor balance of the current in the potential coaxial ports of the bridge $\mathrm{H_{POT}}$ and $\mathrm{L_{POT}}$, i.e. the bridge "ignored" the voltage drop in the shield of the standard. Although the bridge ports contain small coaxial chokes that should improve current balance in the ports, they became effective only at higher frequencies. At low frequencies, the bridge basically measured in 4T definition, resp. 5T definition shown in Fig. 2 on the left and only at higher frequencies the difference between 4TP and 5T definition started to disappear. This effect can be suppressed by insertion of external coaxial chokes to the E4980A ports (green trace). In this case the E4980A bridge matches reference digital 4TP bridge much better. However, long cables wound on the chokes introduce other errors, so the size of chokes is limited. The other RLC bridge models acts similarly. This effect

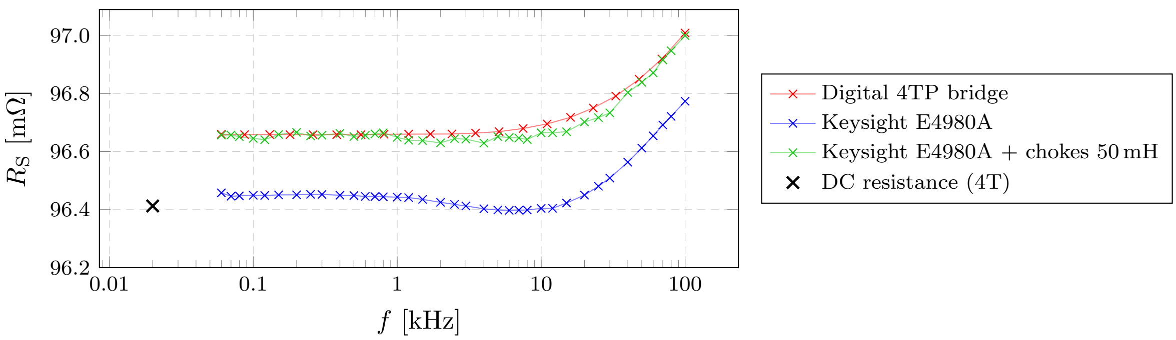


Figure 4: Example of impedance measurement errors caused by shield impedance ($Z_{\mathrm{G}} \approx 230$ µΩ) of poorly designed standard when measured by bridge with and without balanced currents in its coaxial ports.

may not be apparent for a first look, but it is known to cause a lot of confusion when such standards are being used by different labs on different bridges. E.g. the calibration lab performs calibration in true 4TP definition and user will try to use them for ordinary RLC bridges which inevitably results into large offsets of real component of impedance. Therefore, low impedance standards of construction shown in Fig. 3 are rarely used below some 10 Ω. It is generally not recommended even with true 4TP bridge setups, because the internal impedance $\hat{Z}$ may be very stable in order of ppm/K, but the voltage drop between the ports may not due to unstable shield and/or contact resistances. Therefore, the effect is often suppressed by modified connection of the standard's grounds as shown in Fig. 5. By splitting the ground circuit for the current ports $\mathrm{H_{CUR}}$ and $\mathrm{L_{CUR}}$ and potential ports $\mathrm{H_{POT}}$ and $\mathrm{L_{POT}}$, the current path return current $\hat{I}_{\mathrm{CH}}$ no longer flows via the shield impedance $\hat{Z}_{\mathrm{G}}$ and thus there is minimized voltage drop $\hat{U}_{\mathrm{G}}$. It will never be zero, because there are mutual couplings inside the standard, but it will be greatly reduced. In some cases the grounds are connected in the middle as shown in Fig. 5, but in some cases the grounds are totally split. In conclusion, when measuring low impedances, the only reasonable advice is to always check the method of connection of grounds of 4TP standards before they are used and preferably avoid low impedance types when all four BNCs are simply mounted on common metal plate.

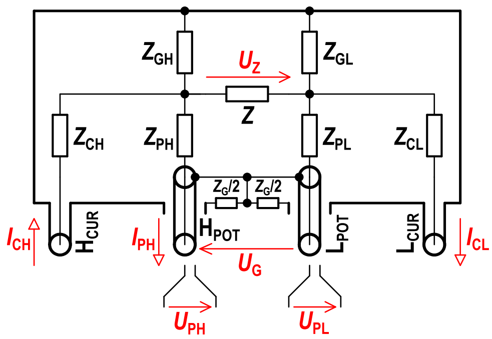


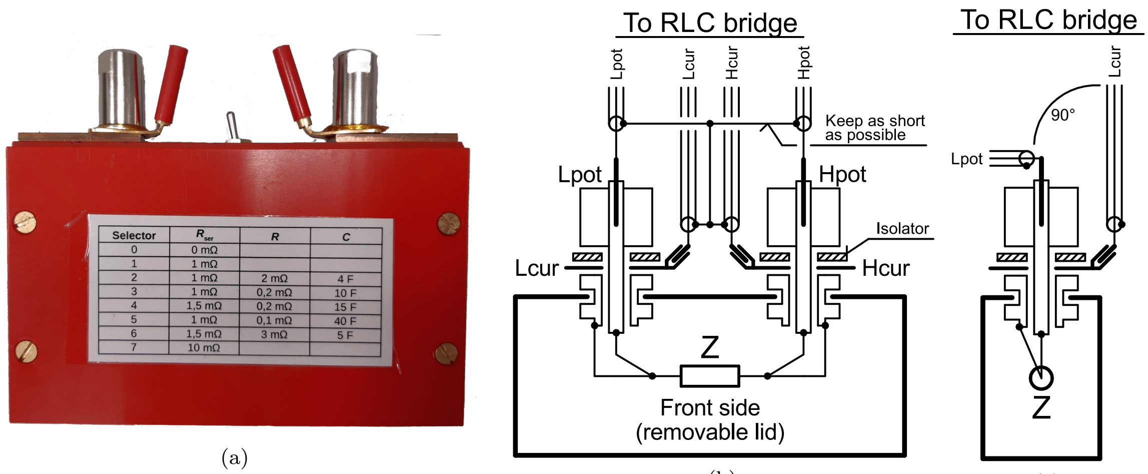
Figure 5: 4TP standard with suppressed shield impedance.

1.1 Adapters

Unavoidable part of any impedance measurement is proper interconnection between the bridge and calibrated device (UUT). Whereas RLC bridges often use four BNCs for 4TP measurements, the actual components to be measured are typically two terminal (2T) devices such as resistor, capacitor or battery as in case of EIS measurements. Obviously, an adapter must be used to traverse between the two types of physical connections. Some of the examples were shown in [6]. The main problem for the higher impedances and frequencies below say 100 kHz lies in avoiding capacitive leakage between High and Low terminals. That is relatively easy to solve by insertion of metallic shields connected to the measurement ground of RLC meter (guarding). However, for low impedance measurements, the situation is more complex. It is necessary to take into account not only series impedances of the interconnection joints, but also mentioned ground impedance problems and mutual couplings between cables and leads. There are several techniques how to minimize these effects.

1.1.1 4TP to 2/4-wire interfacing

Most common situation is connection of 4TP bridge equipped by four coaxial ports to two terminal (2T) or four terminal (4T) UUT. Practical example is shown in Fig. 6. UUT is impedance simulator box in



(a) (b) (c)

Figure 6: Example of adapter between two terminal standard and 4TP bridge. a) Photo, b) front view, c) side view.

a shape of larger lithium cell with two screw terminals. Practical inner solution of the standard is not relevant, however the important aspect are its terminals. Each of the terminals was split into two separate coaxial terminals. The inner one is used for potential measurement whereas the outer one is used for supplying measurement current. In order to connect such standard to a 4TP bridge, the H_{CUR} and L_{CUR}

coaxial cables are connected to the current terminals and their coaxial shields are interconnected to ensure proper return path for the measurement current. Important rule is to keep the non-coaxial parts of the connection as short as possible as well as the ground joint between the two cables. The non-coaxial part of the connection should be rigid, so it cannot change geometry easily. The potential cables H_{POT} and L_{POT} are connected in the same manner, i.e. as short as possible non-coaxial path to the terminals and their coaxial grounds connected together. Both ground joints between the H_{CUR}-L_{CUR} and H_{POT}-L_{POT} should be connected together by another ground lug taped roughly in the middle. The four coaxial grounds should never be connected to a star configuration nor mounted on common conductive place as it would introduce the mentioned problem of current return path impedances. The mutual coupling between the potential wires and current wires can be further reduced by bending one of those pairs into 90 degrees angle. This is especially helpful for the non-coaxial parts of the adapter, but it will help even for the coaxial ones since the currents in the cables are never fully balanced and thus still sensitive to mutual couplings.

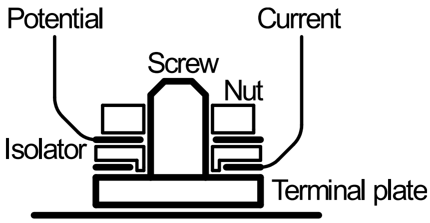


Figure 7: Example of connection of potential and current test leads to screw terminals.

This example showed connection of standard with specially designed standard with split potential and current terminals. However, it is possible to make similar connection even with actual cell with screw terminals using cleverly made isolating washers as is shown in Fig. 7. Even if the central screw is connected to the base plate of terminal, the isolating washer shortens the common path of current and potential sensing, so the reference plane of measurement shifts closer to the actual cell.

1.1.2 4-wire interfacing

When the standard shown in Fig. 6 is connected to EIS meter equipped by only four non-coaxial leads, the connection may be made according to Fig. 8. In this case the magnetic interference between the current leads and potential leads can be minimized by tightly twisting the current leads and splitting them just before connection to the UUT. The potential lugs can be twisted as well, however the terminals are quite far apart in this case, so there will be still quite long non-twisted portion of the connection. In this particular case it is not even possible to bend the plane of potential wires by 90 degrees as it comes out of the same cable as the current leads. So here it is possible to use principle of symmetry. If the wiring is made symmetrical as in the Fig. 8, the mutual couplings to both potential leads should be roughly equal and thus subtract. The UUT shown in the example in Fig. 6 contains switch for several ranges including internal SHORT correction. The SHORT correction enables subtraction of residual mutual inductances of the adapter, however if it should work properly, the geometry of the adapter wiring must not change when switching the particular ranges of the UUT.

1.1.3 4-wire to 4TP interfacing

Whereas interfacing 4TP to 4-wire seems to be straightforward, the opposite direction is usually not possible without limitations. Connection of 4TP standard (UUT) to 4T bridge equipped by plain current and potential leads may be needed when the UUT is calibration standard to be used to correct RLC bridge's errors (LOAD correction). It is theoretically possible under several conditions. First, UUT grounds must be connected according to Fig. 5, so there should be minimized difference between 4T and 4TP connections. Second, if UUT was calibrated in 4TP defining conditions, it is at least necessary to ensure current return path via the shield of UUT via the H_{CUR} and L_{CUR} ports as was shown in Fig. 9. Lack of this current return path would significantly change reactance of the UUT. However, whenever it is possible, the UUT should be calibrated in the same connection instead of relying on small difference between 4TP connection and Fig. 9.

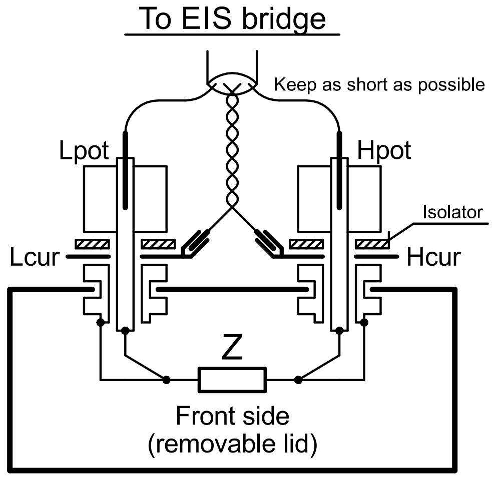


Figure 8: Example of adapter between two terminal standard and 4T/5T bridge.

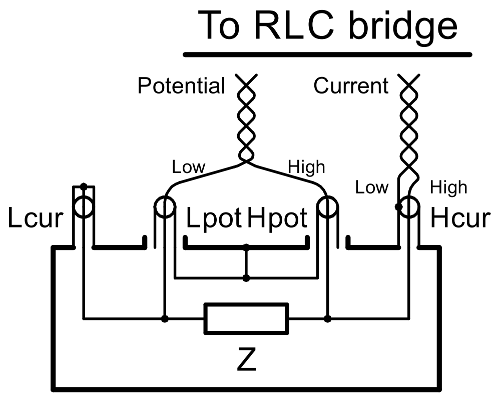


Figure 9: Possible connection of 4TP standard to 4T bridge using plain potential and current leads.

1.2 Concept of SHORT correction

In impedance metrology there are usually two ways of expressing impedance: (i) absolute and (ii) relative. First, most common in primary labs and/or for use with true 4TP bridges, is "absolute" impedance according to 4TP defining conditions. The impedance is given exactly as measured at the reference plane of standard's ports under three conditions: Zero current from $\mathrm{H_{POT}}$ port, zero voltage at $\mathrm{L_{POT}}$ port and fully balanced currents in all ports. However, the 4TP connection is rarely used for practical measurements of impedance. Some kind of adapter is used to traverse from bridge connectors to UUT as described earlier. Such adapter always introduces some parasitic components as shown in model in Fig. 10. The parasitics comprise from series impedance R_S and L_S of non-four wire section of the adapter and combined mutual couplings M_EF in the wiring of the adapter. Both form effective residual series impedance $\hat{Z}_\mathrm{S}$ which adds up to the measured impedance $\hat{Z}_\mathrm{X}$ of the UUT. Therefore, for practical measurements, the RLC bridge/EIS meter always implements some kind of zeroing of effective series impedance of terminals (SHORT correction) and effective parallel shunting admittance between terminals (OPEN correction). The OPEN correction is mainly relevant only for high impedances, whereas SHORT correction for low impedances. The SHORT correction itself is straightforward:

$$\hat{Z}_\mathrm{X} = \hat{Z}_\mathrm{EF} - \hat{Z}_\mathrm{S}, \tag{7}$$

where $\hat{Z}_\mathrm{EF}$ is total measured impedance, $\hat{Z}_\mathrm{S}$ is interface effective series impedance and $\hat{Z}_\mathrm{X}$ is "true" impedance of the UUT. The OPEN and SHORT corrections allow, up to some level, to eliminate unwanted parasitic impedances in the adapter between the bridge and UUT. Practical problem is of course realization of SHORT. It is relatively straightforward to make "ideal" SHORT module in 4TP connection in Fig. 11. However, in other configurations, such as two-terminal with terminals far apart it is impossible, because shorting bar will have residual impedance by itself and also mutual coupling in the wiring of interface which will result into some effective combined impedance. It is also not possible to e.g. screw two wires together, because change in geometry of the adapter wiring would again lead to change of its effective mutual couplings. Therefore, for practical reasons, it is common to express impedance of UUT as relative to residual impedance of some well defined SHORTing module, which will then be used by user of the UUT standard itself. Every calibration certificate of an impedance standard should clearly mention if the expressed impedance is related to particular SHORT or absolute one. If not mentioned and procedure mentions no SHORT standard in the list of equipment, it is almost always the absolute mode. However, for low impedance measurements it should be clarified with certificate issuing institution.

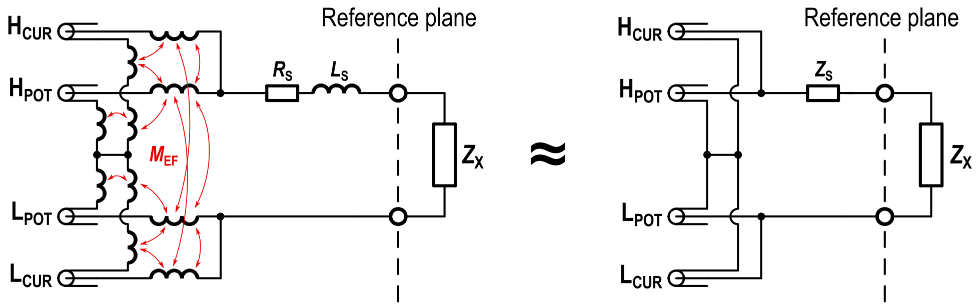


Figure 10: Parasitic components of adapter (left) and equivalent SHORT correction model (right).

The SHORTing standard is internally constructed in such a way it should exhibit minimal effective impedance. If made properly in 4TP connection, the residual impedance can be even below 1 µΩ at low frequencies. It is often considered as "ideal" zero despite its residual impedance grows with frequency. Therefore, as mentioned above, it is good practice to always calibrate especially low impedance standards relative to particular SHORTing standard and express the values in calibration certificate relative to residual impedance of SHORTing standard. This ensures compatible measurement conditions in calibration lab and user of the standard. Another type of zeroing standard is so called 0 Ω standard. The difference

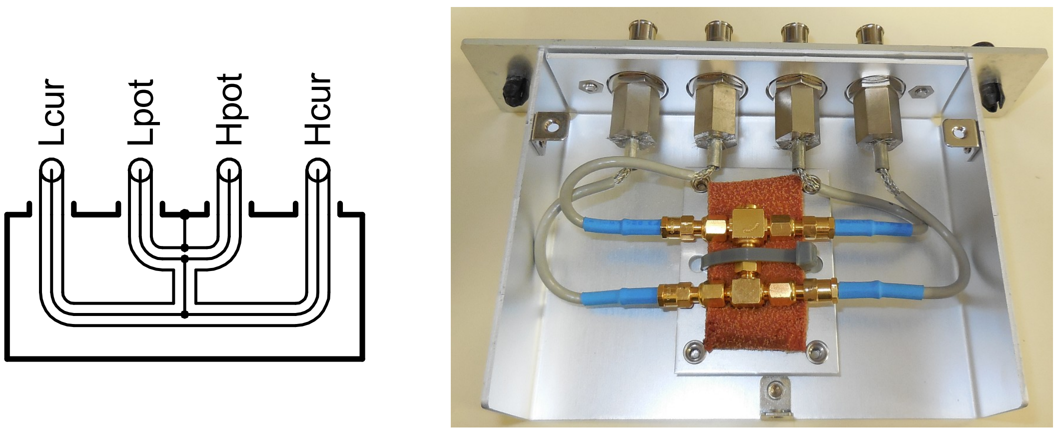


Figure 11: 4TP coaxial cable connection of SHORT correction (left) and practical example of SHORT module from Hewlett Packard 16074A set.

between SHORT and 0 Ω standards is the 0 Ω standard is not trying to reach zero impedance. Instead, it is internally designed with some kind of shorting bar/joint in identical geometry as the other standards of the set under assumption the residual resistance and especially reactance will be identical. Therefore, the relative impedance will have orders of magnitude lower series inductance component. The bridge needs not to make any other step to use 0 Ω standard. The zeroing (SHORT correction) is simply performed with the 0 Ω standard connected instead of SHORT.

Example of 4TP SHORT correction cables connection is shown in Fig. 11. Note the coaxial connectors are mounted via isolation washers, so the return current flows via the cables inside the box instead of metal case. Otherwise there would be significant mutual coupling between the parallel sections of the cables and thus certain effective inductance. Practical example of old Hewlett Packard HP16074A standard is shown in Fig. 11 on the right. It is also common to connect the same SHORT topology externally using BNC cables and T-adapters. Modern solution to SHORT (and the standards in general) is use of strip lines on printed circuit boards as shown in Fig. 12. Use of PCB is practical due to much better geometrical repeatability and also price.

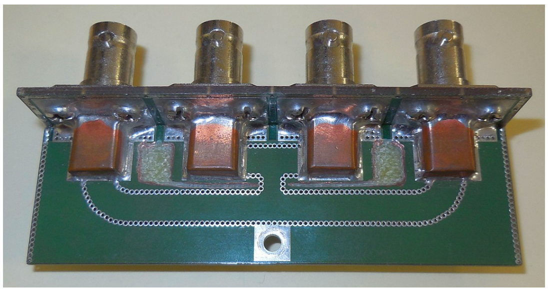


Figure 12: SHORT module made using strip lines on four layer PCB.

Visually interesting example of impedance standards set built with zero $0\,\Omega$ correction is Hewlett Packard 16074A. Detailed picture of internal structure is shown in Fig. 13. Geometry of $0\,\Omega$ and $100\,\mathrm{m}\Omega$ stayed the same, except the thin ridge in the middle which makes the resistive element. All four BNCs are mounted directly to metal plate, so there is ground impedance, but it should be roughly the same for all standard in the set, so the effect will be eliminated by the bridge SHORT correction. However, if the bridge would be zeroed by SHORT correction from the set (Fig. 11), the resulting relative impedance would be hardly usable.

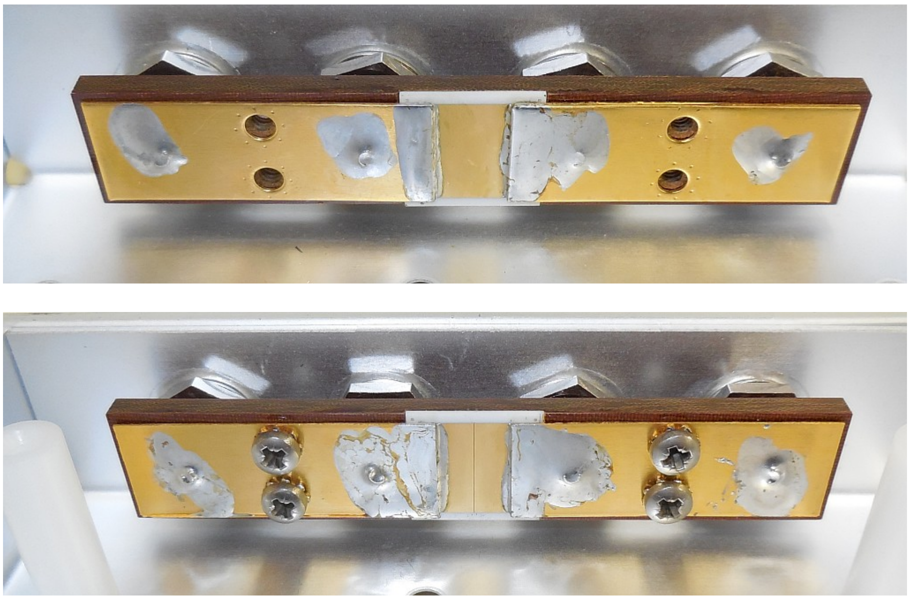


Figure 13: Inside of Hewlett Packard 16074A impedance standards set. Top: $0\,\Omega$ standard with solid metal shorting plate. Bottom: $100\,\mathrm{m}\Omega$ standard.

1.2.1 4-wire short

Whereas short arrangement in 4TP connection is quite straight forward, it is not so simple and effective in 4-wire connection. 4-wire short must be connected in such a way the mutual coupling between potential and current leads is minimized and current flowing via the current leads joint does not produce voltage drop on the potential terminals joint. At the same time, low test leads should be connected together, because impedance bridge may not be able to handle totally floating potential leads. Example of simple connection with banana terminals is shown in Fig. 14 on the left Important is to keep the order so current is not flowing via the potential bananas. Alternatively, it is possible to make a shoring adapter with banana sockets as shown in Fig. 14 on the right. In both cases twisting of the test leads reduces their mutual coupling, so parasitic reactance X_S is minimized.

Twisting the leads is critical in order to achieve low reactance errors. Fig. 15 shows example with typical values of mutual coupling to be expected. The twisted part exhibits almost no mutual coupling even when the twisted bundles lies on each other. Worst case estimate is $M_{EF} \approx \pm 5$ nH per 10 cm of leads, which is roughly $X_{EF} \approx \pm 150\,\mu\Omega$. That is in fact pessimistic estimate. Real coupling when the bundles are at least centimeter apart will be lower than 2 nH. However, when the twisting ends near the short adapter (or UUT), even small loop shown in example in Fig. 15 will have parasitic inductance of $M_{EF} \approx \pm 50$ nH, i.e. $X_{EF} \approx \pm 1.5\,\mathrm{m}\Omega$. That may be already significant offset when large cell impedances are measured. Fortunately, the mutual coupling drops fast, when the potential and current leads are kept at least few centimeters apart.

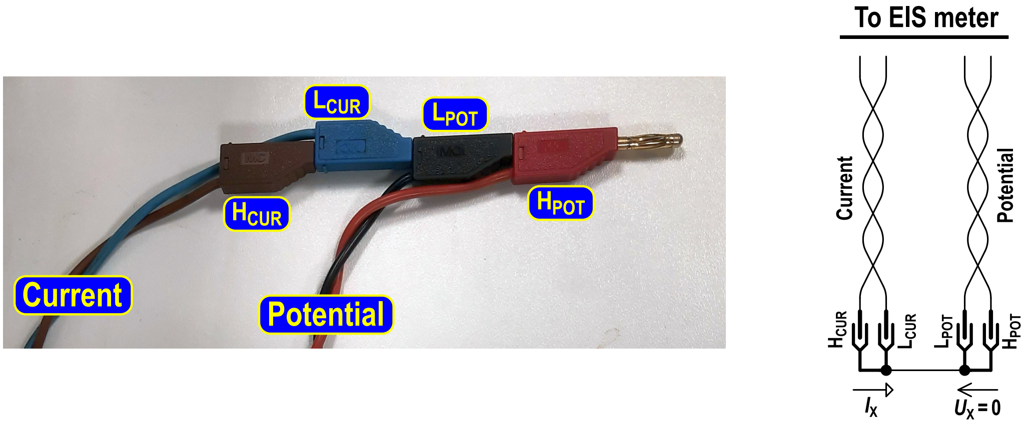


Figure 14: Simple 4-wire short connection with banana test leads: simple banana connection (left), connection via adapter with sockets (right)

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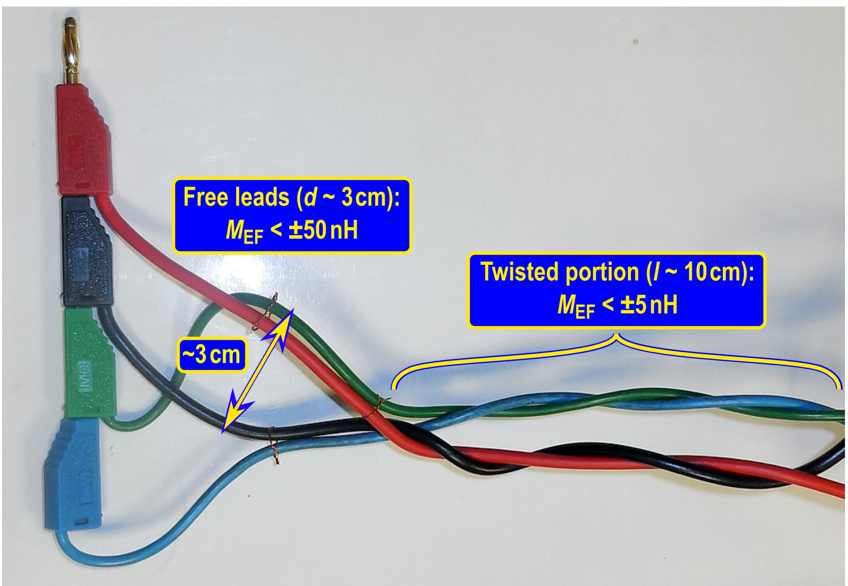

Figure 15: Example of parasitic mutual coupling between 4wire leads.

1.2.2 SHORT correction vs RLC meter setup

The reasons for use of SHORT correction related to external connection of UUT were discussed in previous paragraphs. However, there are also other reasons why RLC meters perform SHORTing. The bridge itself has internal couplings and other errors in its analogue circuits, so it may exhibit considerable errors even with ideal external connections. The SHORT correction suppresses both internal and external sources.

The internal SHORTing procedure of particular RLC meters can differ significantly from model to model. The older RLC bridges can often hold only one of small set of OPEN and SHORT values measured for selected parameters e.g. for a single frequency, single drive level (amplitude of voltage or current) and single range. Hence, the correction has to be remeasured whenever the frequency or drive level was changed. Modern RLC meters are typically able to perform and hold SHORT correction data for discrete set of frequencies spread over the whole operating range and often for each of the affected impedance ranges, however not for each drive level. It is important to note it's possible that the residual internal series impedance errors changes considerably when drive level is changed even within one physical voltage range. Authors of this text observed such effect e.g. on some of the older HP 4284A bridges. Therefore, the OPEN/SHORT corrections should be performed under the same measurement conditions as main measurement. The eventual dependence on the drive level can be easily checked using impedance standard with small current dependence and observing changes in measured impedance when drive level is changed. It is especially relevant to check what happens at boundaries of drive level ranges. E.g. for E4980A, one such boundary is when changing drive level from 1.000 V to 1.001 V (or from 10 mA to 10.01 mA which is equivalent) where internal range is changed. If there is considerable change, it may also lead to problems with automatic level control function (ALC). This function is changing source drive level, so UUT is supplied with actual desired value of voltage or current. Some bridges call this mode constant voltage (CV) or constant current (CC). This function will inevitably change voltage ranges and thus may produce unwanted "jumps" in the measured characteristics. Thus, if the ALC function is to be used, it should not be used with level set near the boundary, so the ranges won't change randomly during the measurement.

Range 1 kΩ	ovld	ovld	ovld	ovld	ovld	ok
Range 300 Ω	ovld	ovld	ovld	ovld	ok	usable
Range 100 Ω	usable	usable	usable	ok	usable	usable
Range 10 Ω	usable	usable	ok	ovld	ovld	ovld
Range 1 Ω	usable	ok	ovld	ovld	ovld	ovld
Range 0.1 Ω	ok	ovld	ovld	ovld	ovld	ovld
Z [Ω]	0 - 0.1	0.1 - 1	1 - 10	10 - 300	300 - 1k	1k - 3k

Figure 16: Example of measurement ranges of RLC meter (Keysight E4980A). "OK" - optimal measuring range, "usable" - usable measuring range with limited accuracy, "ovld" - overload.

Another important aspect of SHORT corrections is the RLC bridges often have their impedance ranges arranged as in example for E4980A shown in Fig. 16. The boundaries will differ for particular models, but the general concept is usually the same. The low impedance ranges, in the example below 100 Ω, are able to measure impedance from zero up to the range boundary, however they have certain optimal range for best accuracy. The ranges above 100 Ω in the example are capable to measure from the boundary to "infinity". Only exception in the example is the 100 Ω range which can measure in whole range from zero to infinity. On some bridges, the difference between the residual internal SHORT errors are very small for all the lower ranges, however in some bridges there are observable differences, so the SHORT should be performed on the same range that will be used for measurement of UUT.

Finally, it is important to note the RLC bridges usually perform SHORT correction as one quick reading per frequency. If the main measurement of UUT is noisy, e.g. $\pm 10\,\mu\Omega$, then the SHORT correction will exhibit about the same standard deviation. Therefore, even with high averaging of UUT readings, the repeatability will be still by SHORT correction repeatability. Thus, for the most precise measurements, it is good practice to never rely on internal SHORT correction of the RLC meter, but rather measure complex impedance of the SHORT residual manually with averaging to reduce standard deviation and then subtract it manually from the UUT averaged measurements using equation 7. This approach with manually performed SHORT correction itself even without use of LOAD correction can often reduce RLC bridge errors by order of magnitude, when extreme values of impedance are measured.

1.3 Concept of LOAD corrections

Apart from OPEN and SHORT correction, many of RLC bridges designed especially for higher frequencies (usually above 100 kHz) implement some form of so called LOAD correction. The idea of LOAD correction is to connect an impedance standard of known value, enter the value of known complex impedance to the RLC bridge and let the bridge measure its own error at that particular spot in the impedance complex plane (for given frequency, drive level and eventually range). The bridge SW will then use this additional calibration spot to reduce its error when performing measurement of UUT. Depending on the bridge model it is possible to perform multiple of such spot corrections and the bridge then chooses the closest one or interpolates between them to correct particular UUT readings. Note some RLC bridges implement so called "HF correction" or "Gain-phase correction". These are in principle similar, but usually performed with certain prescribed impedance standards, such as 150 pF capacitor for Wayne Kerr 6440B or 100 Ω-100 pF-10 pF set for Wayne Kerr 6530 bridge. These corrections usually takes place only at high frequencies, e.g. above 1 MHz and they should apply to all measurements anywhere in specified measurement range of the bridge.

Although LOAD corrections are very relevant at higher frequencies, where the errors introduced by various adapters may be significant, they are certainly not limited to high frequencies. It is beneficial to use the technique for any frequency to reduce bridge own internal errors. The problem of using LOAD correction mechanism integrated in some bridges may be it is not known how does the particular bridge use LOAD correction when the measured value of UUT lies far in the complex plane from the LOAD correction impedance or how the bridge behave if there are e.g. multiple LOAD correction spots with similar modulus of impedance $|Z|$ but different phase angles. The result may be then unpredictable. In such cases and for bridges without LOAD correction mechanism it may be useful to perform LOAD correction manually on the measured complex impedance data. The bridge measurement error for particular range and frequency can be defined by equation:

$$\hat{Z}_{\mathrm{M}} = \hat{Z}_{\mathrm{X}} \cdot \varepsilon_{\mathrm{gain}}(|\hat{Z}_{\mathrm{X}}|, \angle\hat{Z}_{\mathrm{X}}) \cdot e^{j\cdot\varepsilon_{\phi}(|\hat{Z}_{\mathrm{X}}|,\angle\hat{Z}_{\mathrm{X}})} = \hat{Z}_{\mathrm{X}} \cdot \hat{\varepsilon}(|\hat{Z}_{\mathrm{X}}|, \angle\hat{Z}_{\mathrm{X}}) = \frac{\hat{Z}_{\mathrm{X}}}{\hat{c}(|\hat{Z}_{\mathrm{X}}|, \angle\hat{Z}_{\mathrm{X}})}, \tag{8}$$

where $\hat{Z}_{\mathrm{X}}$ is true UUT complex impedance, $\hat{Z}_{\mathrm{M}}$ is complex impedance measured by the bridge, $\varepsilon_{\mathrm{gain}}(|\hat{Z}_{\mathrm{X}}|, \angle\hat{Z}_{\mathrm{X}})$ is bridge gain error (neutral gain is 1.0) and $\varepsilon_{\phi}(|\hat{Z}_{\mathrm{X}}|, \angle\hat{Z}_{\mathrm{X}})$ is bridge phase error and $\hat{\varepsilon}(|\hat{Z}_{\mathrm{X}}|, \angle\hat{Z}_{\mathrm{X}})$ is bridge error in complex form and $\hat{c}(|\hat{Z}_{\mathrm{X}}|, \angle\hat{Z}_{\mathrm{X}})$ is complex correction factor (inverse of error $\hat{\varepsilon}(|\hat{Z}_{\mathrm{X}}|, \angle\hat{Z}_{\mathrm{X}})$). The error $\hat{c}$ is dependent on modulus of measured impedance $|\hat{Z}_{\mathrm{X}}|$ because of RLC bridge non-linearity and it is also dependent on the measured phase angle which may be caused e.g. by crosstalk inside the bridge or asymmetry of its quadrature detector. Detailed characterisation of these dependencies would require sophisticated impedance simulator such as developed in scope of LiBforSecUse project by METAS [4] (original paper on mid-range impedance simulator can be found in [5]). Such approach is usually not possible, so in order to reduce complexity of correction, the error is mostly considered independent at least on the phase angle, so the dependency is reduced to $\hat{\varepsilon}(|\hat{Z}_{\mathrm{X}}|)$. The dependence of bridge error on modulus of measured impedance $|\hat{Z}_{\mathrm{X}}|$ can be eventually ignored as well. In such case the range may be calibrated by one spot chosen to be either at maximum range value or somewhere in the middle. E.g. for E4980A range 10 Ω, which can measure effectively from 1 Ω to 10 Ω, the calibration spot may be 3 Ω. Graphical example of the LOAD correction process with a single calibration spot for entire range is shown in Fig. 17. The usable complex impedance range of the selected bridge range is shown in blue color. Calibration impedance of known value $\hat{Z}_{\mathrm{R}}$ is connected to the bridge and the complex impedance value $\hat{Z}_{\mathrm{C}}$ indicated by the bridge is recorded. Bridge error $\hat{c}$ is calculated:

$$\hat{c} = \frac{\hat{Z}_{\mathrm{R}}}{\hat{Z}_{\mathrm{C}}}. \tag{9}$$

Next, for each UUT measurement within the range, the UUT is connected to the bridge and indicated complex impedance $\hat{Z}_{\mathrm{M}}$ is recorded. Correction factor is applied to obtain actual value of impedance $\hat{Z}_{\mathrm{X}}$:

$$\hat{Z}_{\mathrm{X}} = \hat{Z}_{\mathrm{M}} \cdot \hat{c}. \tag{10}$$

This simple example expects uniform gain-phase error in whole complex plane. When at least the dependency on the modulus of impedance $\hat{c}(|\hat{Z}_{\mathrm{X}}|)$ should be implemented, it is possible to calibrate range

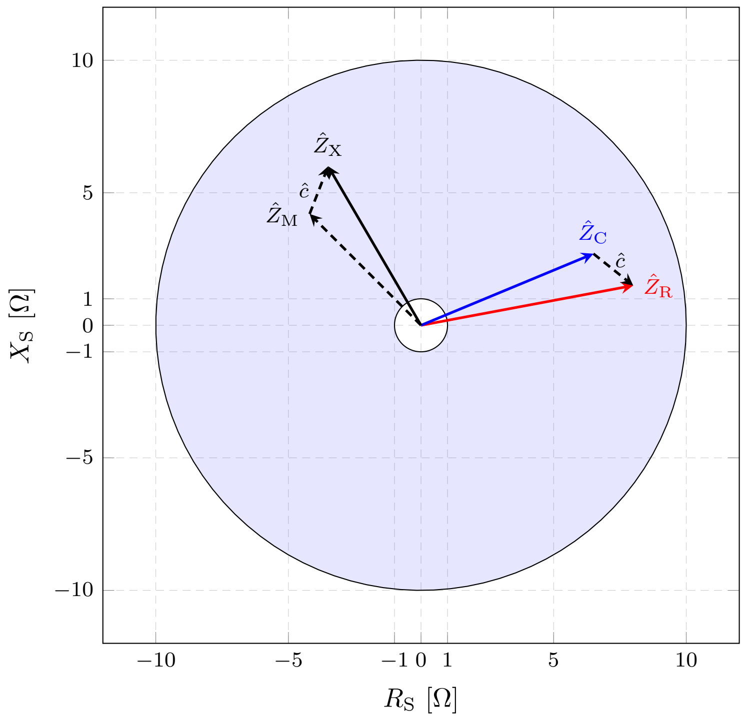

Figure 17: Example of LOAD correction calibration measurements and DUT measurements for range 1 to 10 Ω.

error using several resistance standards displaced in the usable range of $|\hat{Z}|$. For example above, suitable calibration spots should be at least top and bottom of the range, i.e. 1 Ω and 10 Ω resistors. Better option would be 1-3-10 Ω. This process would be the same as shown in Fig. 17, except two, resp. three calibration factors $\hat{c}_1$, $\hat{c}_3$ and $\hat{c}_{10}$ would be obtained. The correction factor measured with the standard of the nearest modulus of impedance $|\hat{Z}_R|$ to the impedance of UUT will be chosen for correction or the correction factors may be interpolated based on the UUT modulus of impedance $|\hat{Z}_M|$.

1.4 Automated SHORT/LOAD corrections

The process of manually performed SHORT and LOAD corrections may be a bit tedious process when it should be performed by hand or by placing formulas to Excel every time measurement is done. It is usually performed automatically by some specialized SW tool or calculation script including estimation of uncertainties. In some cases it may be even possible to perform LOAD corrections once and reuse the calculated correction factors for several months unless the wiring (adapter) was changed. The stability of the bridge errors usually allows it. Only SHORT for the UUT measurement is typically needed to be remeasured just before/after measurement as there is always some drift in time and with temperature.

One such automatic RLC bridge errors correcting script was designed and experimentally used in scope of the LiBforSecUse project. It is a set of Excel sheets [2]. The concept of this Excel corrections is following:

1. Fill in list of available calibration impedance standards to sheet “Ref Z list”.
2. Fill in calibration data of each reference impedance standard into sheet “Ref Z”.
3. Measure value of each of the standard at each of the required ranges and fill in the results to sheet “Cal Data”. This sheet will automatically load reference impedance value from sheet “Ref Z” and calculate correction factors.
4. Connect UUT and perform the measurements as usual and fill in the results into sheet “Measurement”. The sheet will try to load correction factors and correct the measured data.

Row	Range	f	Measured Z: Rs	ua(Rs)	Xs	ua(Xs)	Rs-Xs unit
20	Ohm	Hz	Ohm	Ohm	Ohm	Ohm	Ohm
21	100 m	100	-37.398 08	0.000 00	82.705 74	0.001 26	m
22	3 m	0.01	-2.779 67	0.001 27	0.775 91	0.000 03	m
23	3 m	0.05	-1.552 00	0.001 67	-2.531 73	0.001 78	m
24	10 m	5000	3.158 10	0.001 42	0.839 64	0.001 39	m
25	3 m	2000	0.861 86	0.000 83	-0.307 24	0.001 29	m
26	3 m	10	1.358 81	0.001 80	-0.530 37	0.001 21	m
27	3 m	0.02	2.189 52	0.001 16	0.958 92	0.001 94	m
28	10 m	500	4.840 81	0.001 37	-3.239 30	0.000 27	m
29	3 m	0.2	0.141 72	0.001 74	-2.340 66	0.001 45	m
30	10 m	0.1	-6.128 95	0.000 24	-2.979 03	0.000 10	m
31	1 m	200	-0.231 76	0.000 18	0.460 35	0.000 29	m
32	100 m	10	-76.997 09	-0.000 65	50.190 39	0.001 88	m
33	3 m	10	-0.870 29	0.000 93	-0.398 88	0.001 57	m
34	3 m	200	-0.832 58	0.001 48	-0.789 29	0.000 36	m
35	3 m	0.1	2.031 71	0.001 01	1.238 58	0.000 48	m
36	3 m	5000	1.189 16	0.001 78	-1.520 11	0.000 00	m
37	100 m	1	-12.001 18	0.000 27	-3.710 81	0.001 83	m
38	10 m	20	-4.088 73	0.001 27	1.681 98	0.000 08	m
39	1 m	0.02	0.334 08	0.000 23	-0.617 37	0.001 79	m
40	10 m	2000	-9.641 81	0.001 58	-2.907 43	0.000 35	m
41	3 m	10	0.966 45	0.001 19	1.428 69	0.000 05	m
42	10 m	50	0.727 05	0.001 35	-3.272 00	0.000 76	m
43	10 m	0.01	1.230 74	0.000 89	9.898 64	0.000 92	m
44	3 m	0.1	-0.239 25	0.000 17	-1.040 85	0.000 30	m
45	1 m	10	0.472 69	0.000 64	-0.443 52	0.001 63	m
46	1 m	0.1	-0.019 45	0.001 03	-0.008 58	0.000 57	m
47	100 m	0.2	14.805 79	0.001 13	42.896 56	0.000 92	m
48	10 m	10	-1.779 83	0.001 43	2.131 70	0.001 87	m
49	1 m	10	-0.776 18	0.000 76	0.129 13	0.000 82	m
50	3 m	2000	-1.189 89	0.000 08	1.010 27	0.001 04	m
51	1 m	1	0.192 39	0.000 22	0.005 84	0.001 18	m

Row	Measured residual SHORT Z: sh Rs	sh ua(Rs)	sh Xs	sh ua(Xs)	Rs-Xs unit	Corrected Z (results): Fixed Rs	Fixed U(Rs)	Fixed Xs	Fixed U(Xs)		Status
20	Ohm	Ohm	Ohm	Ohm	Ohm	Ohm	Ohm	Ohm	Ohm		-
21	-0.001 10	0.001 52	0.000 65	0.001 32	m	-37.400 00	0.008 67	82.700 00	0.005 06	m	OK
22	0.000 23	0.001 53	0.000 71	0.000 16	m	-2.780 00	0.003 75	0.775 00	0.002 59	m	OK
23	-0.001 68	0.001 83	-0.001 60	0.000 19	m	-1.550 00	0.005 19	-2.530 00	0.004 48	m	OK
24	-0.001 98	0.000 17	0.001 95	0.001 93	m	3.160 02	0.003 23	0.837 99	0.005 30	m	OK
25	0.001 96	0.000 18	0.000 82	0.000 01	m	0.860 00	0.002 10	-0.308 00	0.003 46	m	Extrapolated
26	-0.001 09	0.001 36	0.001 74	0.000 73	m	1.360 00	0.004 45	-0.532 00	0.005 01	m	OK
27	-0.000 40	0.000 62	-0.001 13	0.000 92	m	2.190 00	0.003 37	0.960 00	0.004 70	m	OK
28	0.001 47	0.001 37	0.000 95	0.000 34	m	4.840 00	0.003 05	-3.240 00	0.002 78	m	OK
29	-0.001 20	0.000 08	-0.000 69	0.000 01	m	0.143 00	0.006 10	-2.340 00	0.002 93	m	OK
30	0.001 21	0.001 92	0.000 53	0.000 63	m	-6.130 00	0.003 79	-2.980 00	0.004 53	m	OK
31	0.000 24	0.001 78	-0.001 65	0.000 96	m	-0.231 99	0.003 18	0.462 00	0.002 62	m	OK
32	0.001 69	0.000 01	-0.000 32	0.001 24	m	-77.000 00	0.004 70	50.200 00	0.006 47	m	OK
33	-0.000 29	0.000 58	-0.000 98	0.000 84	m	-0.870 00	0.002 96	-0.398 00	0.004 30	m	Extrapolated
34	-0.001 47	0.000 23	0.000 66	0.000 68	m	-0.831 00	0.002 60	-0.790 00	0.002 62	m	OK
35	0.001 64	0.001 15	-0.001 33	0.000 24	m	2.030 00	0.003 40	1.240 00	0.004 36	m	OK
36	-0.000 81	0.001 46	-0.000 08	0.001 91	m	1.189 96	0.004 58	-1.520 00	0.004 42	m	OK
37	-0.000 37	0.001 43	-0.001 87	0.000 33	m	-12.000 00	0.003 16	-3.710 00	0.004 42	m	OK
38	0.001 09	0.000 73	0.001 65	0.001 14	m	-4.090 00	0.003 47	1.680 00	0.005 64	m	OK
39	0.001 11	0.000 34	-0.000 40	0.000 96	m	0.333 00	0.003 42	-0.617 00	0.003 54	m	OK
40	-0.001 96	0.001 35	0.001 81	0.000 42	m	-9.640 01	0.004 07	-2.909 99	0.004 80	m	Extrapolated
41	0.000 34	0.000 93	-0.001 17	0.001 28	m	0.966 00	0.004 57	1.430 00	0.003 68	m	OK
42	0.001 33	0.000 23	-0.001 70	0.001 97	m	0.726 00	0.006 04	-3.270 00	0.004 27	m	OK
43	0.000 09	0.000 82	-0.000 38	0.001 63	m	1.230 00	0.003 09	9.900 00	0.003 73	m	OK
44	-0.001 13	0.000 48	-0.000 78	0.001 54	m	-0.238 00	0.003 55	-1.040 00	0.003 10	m	OK
45	-0.001 36	0.000 71	-0.001 54	0.000 95	m	0.473 98	0.003 20	-0.442 02	0.003 24	m	OK
46	-0.001 55	0.000 75	-0.001 98	0.000 61	m	-0.017 90	0.002 39	-0.006 60	0.001 89	m	OK
47	0.001 85	0.000 06	-0.001 79	0.001 62	m	14.800 00	0.008 43	42.900 00	0.004 46	m	OK
48	-0.000 05	0.001 25	0.001 51	0.000 49	m	-1.780 00	0.004 82	2.130 00	0.004 55	m	Extrapolated
49	0.001 86	0.001 85	-0.000 81	0.000 88	m	-0.778 00	0.003 94	0.130 02	0.003 21	m	OK
50	-0.000 05	0.001 70	0.000 26	0.000 88	m	-1.190 00	0.003 90	1.010 00	0.004 16	m	OK
51	0.001 39	0.000 34	0.000 18	0.001 35	m	0.191 00	0.000 84	0.005 68	0.003 64	m	OK

Info | Measurement | Cal Data | Ref Z | Ref Z list

Připraven

Figure 18: EIS/RLC bridge errors corrections using XLS sheets.

More detailed description of the usage is directly in the sheets. This set of sheets is equipped by simple interpolator, so it can handle multiple reference impedance spots per range and interpolate the closest one. However, it is not designed to handle e.g. combined resistive and capacitive spots for the same range. It is also not generally applicable for EIS meters that do not incorporate manual impedance ranging option. In such cases it is not known where the transitions between the ranges are and thus the correction may be measured on one range, whereas the measurement of UUT at another. Applying such correction under these uncertain conditions may actually result even to increase of error.

Note the correct function of this set of sheets was validated by a GNU Octave script that simulates the calibration and UUT measurements.

1.4.1 Example of corrections

The calculation sheet was tested practically with RLC bridge Keysight E4980A. Range 100 Ω was chosen and corrected by a pair of resistors of values 10 Ω and 100 Ω. Next, UUT of nominal value 30 Ω was measured and its measurement corrected. Absolute deviation before and after correction are shown in Fig. 19. The real component exhibited very low errors even before corrections which is not unusual with this type of bridge. The correction did not helped much. It seems there is linearity limit of the range around 30 to 40 µΩ/Ω. On the other hand, the method greatly improved phase errors expressed as reactance X_S measurement. The errors dropped below 140 µΩ, which is below 5 µΩ/Ω of impedance modulus $|Z|$. Similar results were obtained with 10 µF capacitor measurement shown in Fig. 20. No significant improvement was observed on main component C_P, however angular errors (loss factor D) dropped drastically to order of microradians.

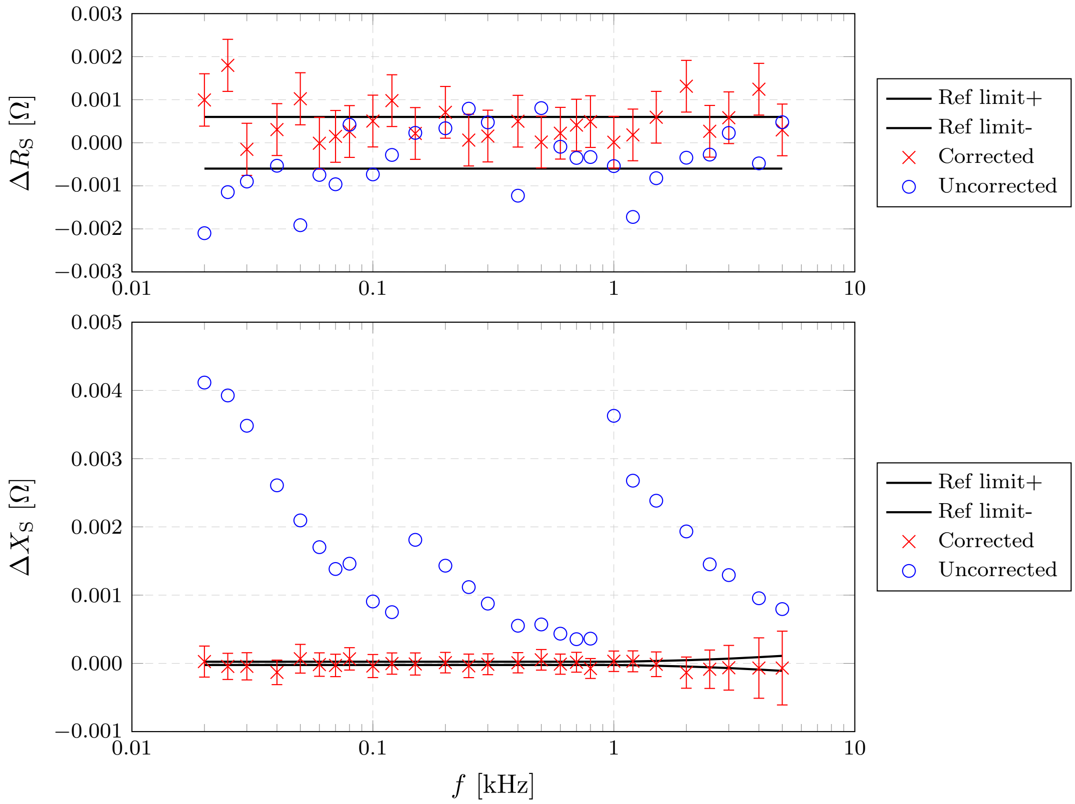

Figure 19: Example of measurement errors of 30 Ω resistance standard using Keysight E4980A with range 100 Ω corrected by pair of standard of values 10 Ω and 100 Ω.

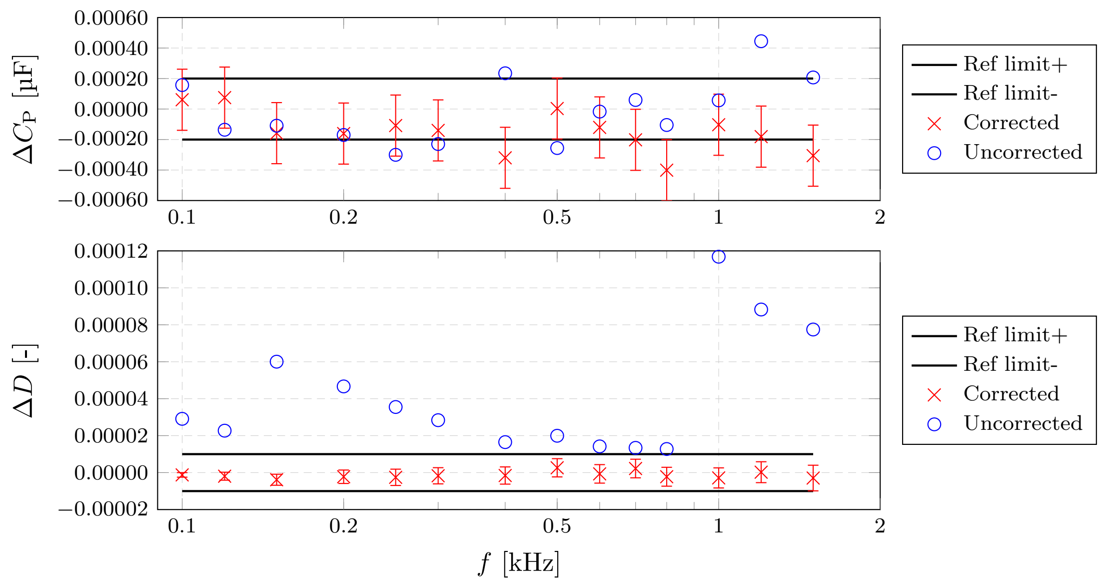

Figure 20: Example of measurement errors of 10 µF capacitance standard using Keysight E4980A with range 100 Ω corrected by pair of standard of values 10 Ω and 100 Ω.

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