Effective Impedance Measurement
Using OPEN/SHORT/LOAD
Correction

Application Note 346-3
**Introduction**

Generally, impedance measurement instruments have a reference plane to define the measurement accuracy at the UNKNOWN terminals of its front panel. HP impedance measurement instruments have a cable length correction function which is applicable for defining the reference plane at the end of the HP test leads. In the actual measurement, a test fixture is connected to the reference plane. Test fixtures degrade the total measurement accuracy by their residual impedance. To improve this degradation, error correction should be applied. The OPEN/SHORT correction is the most popular correction technique used in recent impedance measurement instruments. But when complicated residuals exist (for example, when a scanner or a handler is used), or when using an extension cable whose length cannot be compensated with the cable length correction function, the OPEN/SHORT correction cannot minimize error sufficiently. To minimize these errors, the OPEN/SHORT/LOAD correction is very effective. This application note describes effective impedance measurements using the OPEN/SHORT/LOAD correction.

**How OPEN/SHORT/LOAD correction differs from OPEN/SHORT correction**

Here we compare the principle of the OPEN/SHORT/LOAD correction with the OPEN/SHORT correction.

1. **OPEN/SHORT correction**

   In the OPEN/SHORT correction, the residuals of a test fixture can be modeled as an equivalent circuit shown in Figure 1.

   ![Figure 1. OPEN/SHORT Correction Model](image)

   Since Zs << 1/Yo, stray admittance Yo can be measured when the test terminals are open. Similarly residual impedance Zs can be measured when the test terminals are shorted. Using this correction data, Device-Under-Test (DUT) measurement data Zm can be compensated with the following equation. Then a true value, Zdut, can be derived from Zm by removing the residuals of a test fixture.
\[
Z_{\text{dut}} = \frac{Z_m - Z_s}{1 - (Z_m - Z_s)Yo}
\]

where,
- \(Z_{\text{dut}}\): True value of DUT
- \(Z_m\): Measurement value of DUT
- \(Yo\): Admittance of OPEN condition
- \(Z_s\): Impedance of SHORT condition

(Note that each parameter has real and imaginary components.)

As it has been shown, simple measurement errors can be mathematically compensated by using the OPEN/SHORT correction. However, this specific technique is usable only when performing measurements under the following test conditions:

- Using an HP test fixture
- Measurements at the front panel terminals
- Measurements using an HP test cable compensated for electrical length

There are numerous test conditions where complicated impedance parasitic cannot be modeled as the simple equivalent circuit in Figure 1. The OPEN/SHORT correction will not truly compensate for errors introduced in the following test situations:

- Scanner/multiplexer/matrix switches
- Component handlers
- Custom-made test fixture
- Non-standard length cable test leads
- External DC bias circuitry
- Balun transformer
- Additional filters and amplifiers

In addition, the OPEN/SHORT correction has the following severe limitations:

- Not able to correlate measurement values from different test instruments
- Not able to improve measurement repeatability

To solve these test limitations and issues, the OPEN/SHORT/LOAD correction is necessary.

2. OPEN/SHORT/LOAD correction

The OPEN/SHORT/LOAD correction requires the measurement data of a standard DUT with known values in addition to the OPEN/SHORT measurement data. The residuals of a test fixture can be defined as a four-terminal network expressed with A, B, C, D parameters as shown in Figure 2.
With the assumption that a DUT with an impedance of $Z_2$ is connected to the front panel terminals, the instrument would measure an impedance value of $Z_1$. The following relationship defines $Z_1$.

Given: $Z_1 = \frac{V_1}{I_1}$ and $Z_2 = \frac{V_2}{I_2}$

$$Z_1 = \frac{AV_2 + BI_2}{CV_2 + DI_2} = \frac{AZ_2 + B}{CZ_2 + D}$$

The parameters of A, B, C and D can be removed when using the following definitions:

- $Z_o$: Measured value when the instrument terminals are open.
- $Z_s$: Measured value when the terminals are shorted.
- $Z_{sm}$: Measured value of the standard DUT when connected to the test setup.
- $Z_{std}$: True (or expected) value of the reference DUT.
- $Z_{xm}$: Measured value of DUT.
- $Z_{dut}$: Corrected value of DUT.

All of the analysis yields an equation that corrects for impedance parasitics:

$$Z_{dut} = \frac{Z_{std}(Z_o-Z_{sm}) (Z_{xm}-Z_s)}{(Z_{sm}-Z_s) (Z_o-Z_{xm})}$$

(Note that each parameter has real and imaginary components.)

The OPEN/SHORT/LOAD correction function is built into the following HP LCR meters/analyzers:

- HP 4263B
- HP 4278A
- HP 4279A
- HP 4284A
- HP 4285A
- HP 4286A
- HP 4291B
- HP 4395A with opt. 010 and HP 43961A
- HP 4396B with opt. 010 and HP 43961A
Otherwise, when using other LCR meters or analyzers, a computer can be programmed to make the OPEN/SHORT/LOAD corrections through HP-IB.

**Consideration with OPEN/SHORT/LOAD correction**

When performing OPEN/SHORT/LOAD correction, the following points should be considered.

1. **OPEN correction**

   It is important to measure the stray admittance of a test fixture accurately in the OPEN correction. When getting the OPEN correction data, the distance between measurement terminals should be the same as the distance that is required for actually holding the DUT.

2. **SHORT correction**

   It is important to measure the residual impedance of a test fixture accurately in the SHORT correction. When getting the SHORT correction data, the measurement terminals should be shorted or connected to a shorting device. When using the shorting device, the residual impedance must be much less than impedance value of DUT.

3. **LOAD correction**

   In the LOAD correction, selection and measurement of the standard DUT should be considered carefully.

   (1) Selection of standard DUT

   When selecting the standard DUT, there is no restriction that inductor must be used for inductance measurement, or capacitor must be used for a capacitance measurement. Any device can be used if its impedance value is accurately known. It is important to use a stable DUT not susceptible to influences of environment such as temperature or magnetic fields. From this viewpoint, capacitors or resistors are better sited than inductors which are more susceptible to the environment. Especially in the case of measuring low loss (low D, high Q, low ESR) DUTs, it is necessary to use as low loss standard DUT as possible. Since it is difficult to get low loss inductor but easy to get capacitor, low loss capacitors are recommended for the standard DUT.

   (2) Impedance value of standard DUT

   When measuring a DUT’s various impedance values, it is recommended to use a 100Ω to 1kΩ device as the standard DUT. It can be measured accurately by impedance measurement instruments and is not susceptible to contact resistance or residuals. When measuring a DUT of one impedance value, it is recommended that the standard DUT have a impedance value close to that of the DUT. By using a standard DUT, we can reduce the non-linear errors near its
impedance value. However, when the DUT’s impedance value is very low or very high, it is recommended to use a standard DUT of 100Ω or 1kΩ, whose value isn’t close to the impedance of the DUT. When a low or high impedance standard DUT is used, the reference value (described later) of the standard DUT cannot be obtained accurately, and it may cause the abnormal measurement results, not the true value of the DUT.

(3) Referencing the standard DUT

To perform the OPEN/SHORT/LOAD correction, it is necessary to measure the standard DUT for a reference value (known value) beforehand. When measuring it, it is important to use a high accuracy instrument and to set its measurement conditions (such as integration time or averaging time) so that it can measure as accurately as possible. To minimize the measurement error, the standard DUT should be measured using a direct-connected test fixture after performing the OPEN/SHORT correction.

4. Measurement condition of impedance measurement instruments when performing the OPEN/SHORT/LOAD correction

Impedance measurement equipment with the OPEN/SHORT/LOAD correction function will automatically set the measurement condition (such as integration time or averaging time) so that it can perform error correction with highest accuracy.

If performing the OPEN/SHORT/LOAD correction for instruments not equipped with the OPEN/SHORT/LOAD correction function using an external controller, the measurement conditions should be set to measure correction data as accurately as possible.

Example of actual OPEN/SHORT/LOAD correction

Figure 3 shows the measurement example to extend the HP 4285A’s measurement terminal using 16048E(4m cable). In this case, it is necessary to perform the OPEN/SHORT/LOAD correction since the HP 4285A cannot compensate the 4m extension cable with its cable length correction function. Figure 4 shows the comparison of measurement error between 100pF capacitor measurement with the OPEN/SHORT correction and that with
the OPEN/SHORT/LOAD correction. A 47pF capacitor is used as a standard DUT. This measurement result shows the error cannot be minimized sufficiently with the OPEN/SHORT correction, but can be compensated with an OPEN/SHORT/LOAD correction as shown by the plot.

**OPEN/SHORT/LOAD correction with an external controller**

The OPEN/SHORT/LOAD correction can be accomplished with simple key operation when using an impedance measurement instruments equipped with the OPEN/SHORT/LOAD correction function. When using instruments not equipped with the OPEN/SHORT/LOAD correction function, it is possible to perform the OPEN/SHORT/LOAD correction by executing the correction calculation with an external controller. But this method has the following tradeoff problems as the comparison with the correction of a measurement instrument alone.

- Complicated operation
- Slow measurement speed due to data transfer time

Figure 5 shows an example program to execute the OPEN/SHORT/LOAD correction for capacitor measurement using the HP 4194A Impedance Analyzer. In this program, the measurement is performed at one frequency point with a manual trigger mode.

Line 130-190 setting measurement condition.
Line 210-270 Measuring impedance of OPEN condition in G-B mode.
Line 300-330 Measuring impedance of SHORT condition in R-X mode.
Line 350-610 Measuring impedance of the standard DUT after inputting Cs-D or Cp-D value of valued standard DUT.
Line 660-690 selecting DUT mode(Cs-D or Cp-D).
Line 710-1010 Executing correction calculation after measuring impedance of DUT, then displaying the result.
Conclusion

This application note shows the principle of the OPEN/SHORT/LOAD correction and some points to be considered in the execution. With the proper OPEN/SHORT/LOAD correction, measurement comes higher in accuracy.

"Reference" Impedance measurement handbook (5091-3000)
Figure 5. Sample Program for HP 4194A OPEN/SHORT/LOAD Correction

10 ! OPEN/SHORT/LOAD CORRECTION (4194A C-D MEAS)
20 !
30 CLEAR SCREEN
40 OPTION BASE 1
50 DIM Rcor(3),Xcor(3) ! CORRECTION DATA: Zcor(*)=Rcor(*)+jXcor(*)
60 COMPLEX Zcor(10),Zstd,Zxm,Z
70 ! LOAD VALUE: Zstd=|Rstd+j|Xstd
80 ! DUT MEASUREMENT VALUE: Zxm=|Rxm+j|Xxm
90 ! CORRECTED RESULT: Z=R+jX
100 Freq=1.000E+6 ! f=1MHz
110!
120 ASSIGN @Adrs TO 717
130 REMOTE @Adrs
140 !
150 OUTPUT @Adrs:"FNC1" ! IMPEDANCE MEAS MODE
155 OUTPUT @Adrs:"SWMS" ! MANUAL MEAS
160 OUTPUT @Adrs:"MANUAL=1M" ! f=1MHz
170 OUTPUT @Adrs:"TRGM2" ! EXT/MAN TRG MODE
180 OUTPUT @Adrs:"OPWO" ! OPEN OFFSET:OFF
190 OUTPUT @Adrs:"SWTO" ! SHORT OFFSET:OFF
200!
210! << OPEN MEASUREMENT >>
220 OUTPUT @Adrs:"IMP0" ! SET 4194A TO G-B
230 PRINT "MEASURE OPEN (TYPE 'CONT')"
240 PAUSE
250 CALL Measure(G,B,Adrs) ! OPEN MEASUREMENT
260 Rcor(2)=G/(G*G+B)
270 Xcor(2)=B/(G*G+B*8)
280!
290!
300 OUTPUT @Adrs:"IMP2" ! << SHORT MEASUREMENT >>
310 PRINT "MEASURE SHORT (TYPE 'CONT')" ! SET 4194A TO R-X MODE
320 PAUSE
330 CALL Measure(Rcor(3),Xcor(3),@Adrs) ! SHORT MEASUREMENT
340 ! -> Rcor(3),Xcor(3)
350!
360 INPUT "MODE OF LOAD : 1.Cs-D 2.Cp-D "&Mode ! SELECT Cs-D OR Cp-D
370 IF Mode=1 THEN
380 OUTPUT @Adrs:"IMP2" ! SET 4194A TO G-B
390 INPUT "Cs of LOAD=",Cstd ! INPUT LOAD VALUE
400 INPUT "D of LOAD=",Bstd !
410 Xstd=1/(2*PI*Freq*Cstd)
420 Rstd=812*Cstd*812
430 PRINT "MEASURE LOAD TYPE ('CONT')"
440 PAUSE
450 CALL Measure(Rcor(1),Xcor(1),@Adrs) ! LOAD MEASUREMENT
460 END IF
470!
480 IF Mode=2 THEN
490 OUTPUT @Adrs:"IMP0" ! SET 4194A TO G-B
500 INPUT "Cp of LOAD=",Cstd ! INPUT LOAD VALUE
510 INPUT "D of LOAD=",Bstd !
520 Bstd=2*PI*Freq*Cstd
530 Gstd=Bstd*Bstd
540 Rstd=Gstd*Cstd|Gstd*Bstd*Bstd|
550 Xstd=Gstd/Bstd/(Gstd+Bstd*Bstd)
560 PRINT "MEASURE LOAD TYPE ('CONT')"
570 PAUSE
580 CALL Measure(G,B,Adrs) ! LOAD MEASUREMENT
590 Rcor(1)=G/(G*G+B*8)
600 Xcor(1)=B/(G*G+B*8)
610 END IF
620!
630 MAT Zcor= CMPLX(Rcor,Xcor) ! Zcor(*)=Rcor(*)+jXcor(*)
640 Zstd=CMPLX(Rstd,Xstd) ! Zstd=Rstd+jXstd
650!
660!
680 IF Dmode=1 THEN OUTPUT @Adrs:"IMP2" ! Cs-D --> SET 4194A TO R-X
690 IF Dmode=2 THEN OUTPUT @Adrs:"IMP0" ! Cp-D --> SET 4194A TO G-B
700 PRINT "MEASURE DUT (TYPE 'CONT')"
710 PAUSE
720!
730 p:=1
740 WHILE p<0
750 CALL Measure(Bxm,Gxm,Adrs)
760 IF Dmode=1 THEN ! Cs-D
770 Rxm=Gxm
780 Xxm=Bxm
790 END IF
800 IF Dmode=2 THEN ! Cp-D

810  \text{Rx}=\text{G Xm}/(\text{G Xm}^2 \text{G X m} + \text{B Xm}^2 \text{B X m})
820  \text{X Xm} = \text{B Xm}/(\text{G Xm}^2 \text{G X m} + \text{B Xm}^2 \text{B X m})
830  \text{END IF}
840  \text{Z Xm}=\text{COMPLEX}(\text{Rx Xm}, \text{X Xm})
850  \text{Z}=\text{FCalculate}(\text{Zc r}(\text{X}), \text{Zstd}, \text{Z Xm})
860  \text{R}=\text{REAL}(\text{Z})
870  \text{X}=\text{IMAG}(\text{Z})
880  \text{IF Dmode}=1 \text{ THEN}
890  \text{D}=\text{R}/\text{X}
900  \text{PRINT } "\text{Rs},D=", \text{Rs}, \text{D}
910  \text{END IF}
920  \text{IF Dmode}=2 \text{ THEN}
930  \text{D}=\text{R}/\text{X}
940  \text{PRINT } "\text{Q}=", \text{Q}
950  \text{END IF}
960  \text{IF } \text{CONTINUE}(\text{W}=0) \text{ THEN}
970  \text{SUBEND}
980  \text{END WHILE}
990  \text{END}
1000  \text{DEF FCalculate(COMPLEX A(*),COMPLEX B,COMPLEX C)}
1010  \text{COMPLEX D}
1020  \text{D} = \text{B}*(\text{C-A}(\text{X}))*((\text{A}(\text{Y})-\text{A}(\text{Z})))
1030  \text{RETURN D}
1040  \text{SUB Measure(M, N, @Adrs)}
1050  \text{S}=\text{SPOLL}(\text{@Adrs})
1060  \text{OUTPUT @Adrs;"RQS2"}
1070  \text{OUTPUT @Adrs;"TRIG"}
1080  \text{LOOP}
1090  \text{EXIT IF BANDN(DS=FUNCTION(\text{SPOLL}(\text{@Adrs}),2))}
1100  \text{END LOOP}
1110  \text{OUTPUT @Adrs;"MKRA?"}
1120  \text{OUTPUT @Adrs;"MKRB?"}
1130  \text{END}
1140  \text{SUBEND}
### Appendix. Correction Capability of HP Instruments

<table>
<thead>
<tr>
<th>Model No.</th>
<th>Correction Capability</th>
<th>Cable Length Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP 4192A</td>
<td>OPEN/SHORT Correction</td>
<td>0m/1m</td>
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<tr>
<td>HP 4194A</td>
<td>OPEN/SHORT Correction</td>
<td>0m/1m</td>
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<tr>
<td>HP 4195A(*) with HP 41951A</td>
<td>OPEN/SHORT Correction</td>
<td>none (Electrical Length Correction)</td>
</tr>
<tr>
<td>HP 4263A(*)</td>
<td>OPEN/SHORT Correction OPEN/SHORT/LOAD Correction (via HP-IB)</td>
<td>0m/1m/2m</td>
</tr>
<tr>
<td>HP 4263B</td>
<td>OPEN/SHORT/LOAD Correction</td>
<td>0m/1m/2m/4m</td>
</tr>
<tr>
<td>HP 4274A(<em>) /HP 4275A(</em>)</td>
<td>OPEN/SHORT Correction</td>
<td>0m /1m</td>
</tr>
<tr>
<td>HP 4276A(<em>) /HP 4277A(</em>)</td>
<td>OPEN/SHORT Correction</td>
<td>0m/1m</td>
</tr>
<tr>
<td>HP 4278A</td>
<td>OPEN/SHORT/LOAD Correction</td>
<td>0m/1m/2m</td>
</tr>
<tr>
<td>HP 4279A</td>
<td>OPEN/SHORT/LOAD Correction Multi Channel Correction (Opt.301)</td>
<td>0m/1m/2m</td>
</tr>
<tr>
<td>HP 4284A</td>
<td>OPEN/SHORT/LOAD Correction Multi Channel Correction (Opt.301)</td>
<td>0m/1m</td>
</tr>
<tr>
<td>HP 4285A</td>
<td>OPEN/SHORT/LOAD Correction Multi Channel Correction (Opt.301)</td>
<td>0m/1m/2m/4m (Opt.006)</td>
</tr>
<tr>
<td>HP 4286A</td>
<td>OPEN/SHORT/LOAD Correction</td>
<td>none (Electrical Length Correction)</td>
</tr>
<tr>
<td>HP 4291A(*)</td>
<td>OPEN/SHORT/LOAD Correction</td>
<td>none (Electrical Length Correction)</td>
</tr>
<tr>
<td>HP 4291B</td>
<td>OPEN/SHORT/LOAD Correction</td>
<td>none (Electrical Length Correction)</td>
</tr>
<tr>
<td>HP 4395A with Opt.010,43961A</td>
<td>OPEN/SHORT/LOAD Correction</td>
<td>none (Electrical Length Correction)</td>
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<tr>
<td>HP 4396B with Opt.010,43961A</td>
<td>OPEN/SHORT/LOAD Correction</td>
<td>none (Electrical Length Correction)</td>
</tr>
</tbody>
</table>

(*) Obsolete
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