

Optimizing the **ADuCM350** for 4-Wire, Bioisolated Impedance Measurement Applications

INTRODUCTION

The **ADuCM350** is an ultra low power, integrated mixed-signal metering solution that includes a microcontroller subsystem for processing, control, and connectivity. The processor subsystem is based on a low power ARM® Cortex™-M3 processor, a collection of digital peripherals, embedded SRAM and flash memory, and an analog subsystem that provides clocking, reset, and power management capabilities.

The **ADuCM350** has the ability to perform a 2048 point, single frequency, discrete Fourier transform (DFT). It takes the 16-bit analog-to-digital converter (ADC) output as an input and outputs the real and imaginary parts of the complex impedance.

The configurable switch matrix on the **ADuCM350** allows the user to choose from a 2-wire, 3-wire, or 4-wire impedance measurement.

This application note details how to set up the **ADuCM350** to optimally measure the impedance of a resistor capacitor (RC) type sensor, using 4-wire techniques while targeting IEC 60601 standards.

To target the IEC 60601 standard, the **ADuCM350** is used in conjunction with an external instrumentation amplifier, in-amp, (**AD8226**) to complete high precision absolute measurements using a 4-wire measurement technique.

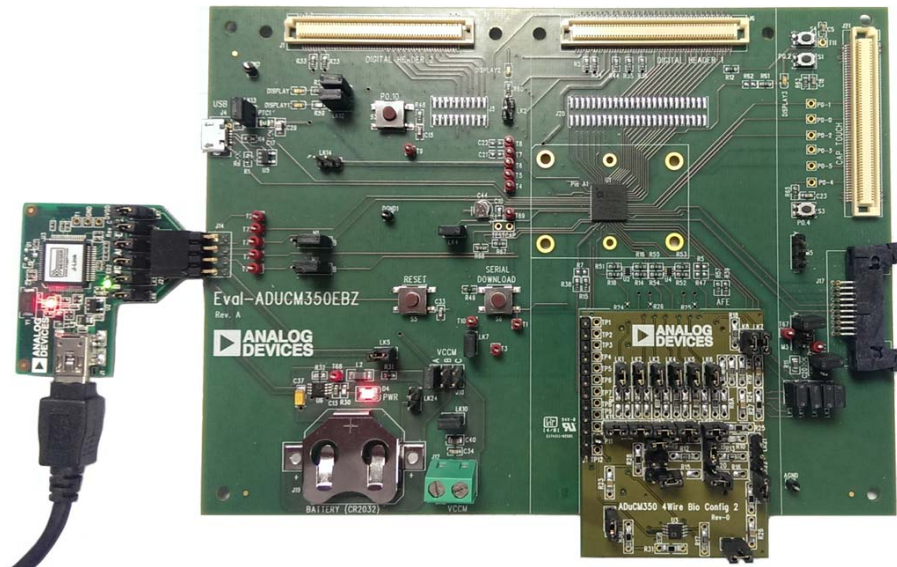


Figure 1. EVAL-ADUCM350EBZ Motherboard and 4-Wire Bioconfiguration Daughter Board

12168B-101

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REVISION HISTORY

2/2018—Rev. 0 to Rev. A

Add Limitations on Use and Liability Section..... 16

4/2014—Revision 0: Initial Version

CONFIGURATIONS FOR MEASURING THE IMPEDENCE OF A SENSOR

The [ADuCM350](#) offers three configurations for measuring the impedance of a sensor: 2-wire system, 4-wire system, and 4-wire bioisolated system.

2-WIRE SYSTEM

In the presence of varying access resistance to the unknown impedance, this configuration provides relative accuracy measurements for impedance magnitude and impedance phase. For further details on optimizing the [ADuCM350](#) for 2-wire impedance measurements, refer to the [AN-1271 Application Note](#), *Optimizing the ADuCM350 for Impedance Conversion*.

The 2-wire system measures the relative accuracy of impedance magnitude and phase.

4-WIRE SYSTEM

This configuration provides absolute accuracy for both impedance magnitude and impedance phase measurements because access resistances are calibrated out. This configuration does not operate where ac coupling capacitors are required to isolate a sensor from the device, that is, capacitors in series with the access resistances. Refer to the [AN-1271 Application Note](#), *Optimizing the ADuCM350 for Impedance Conversion*, for information on optimizing the [ADuCM350](#) for 4-wire measurements.

The 4-wire system measures the absolute accuracy of impedance magnitude and phase; however, isolation capacitors are not allowed.

4-WIRE BIOISOLATED SYSTEM

If isolation capacitors are required between a sensor and the device, an external instrumentation amplifier is required to measure the differential voltage across the sensor. It is not possible for the [ADuCM350](#) to do this measurement as a single chip solution because the isolation capacitors cause instability when included on the sense (P channel and N channel) paths.

The 4-wire bioisolated system measures the absolute accuracy of impedance magnitude in the presence of isolation capacitors; however, this system is not targeted for accurate phase measurements.

BASIC 4-WIRE IMPEDANCE MEASUREMENT

To measure the impedance of an unknown sensor, Z , the following ratiometric measurement technique is employed using the ADuCM350:

1. Measure the impedance of a known precision resistor, R_{CAL} , as shown in Figure 2. An excitation voltage is applied at RCAL 1 with associated D and P switches closed in the switch matrix. The resultant excitation current is measured through RCAL 2, with associated T and N switches closed in the switch matrix. This current is converted to a voltage using the transimpedance amplifier (TIA), where the TIA resistor (R_{TIA}) is optimized for the maximum current seen by the ADC and is converted to a voltage using the ADC. A 2048 point Hann sample is performed on the data to give real and imaginary components of the impedance.
2. Change the switch matrix configuration, as shown in Figure 3, and excite the sensor measuring the response current. The DFT engine now calculates the real and imaginary components of the unknown impedance, Z .

3. Calculate the unknown impedance magnitude on the core using the following equation:

$$Z_{UNKNOWN_MAG} = \frac{Z_{UNK_MAG}}{R_{CAL_MAG}} \times R_{CAL}$$

4. Calculate the unknown impedance phase on the core using the following equation:

$$Z_{UNKNOWN_PHASE} = Z_{UNK_PHASE} - R_{CAL_PHASE}$$

This 4-wire measurement approach to measuring impedances operates if there are no isolation requirements on the sensor. However, if an isolation capacitor, such as C_{ISO} , must be included in series with the access resistor, R_{ACCESS} , in a 4-wire measurement, then a single chip solution is not possible.

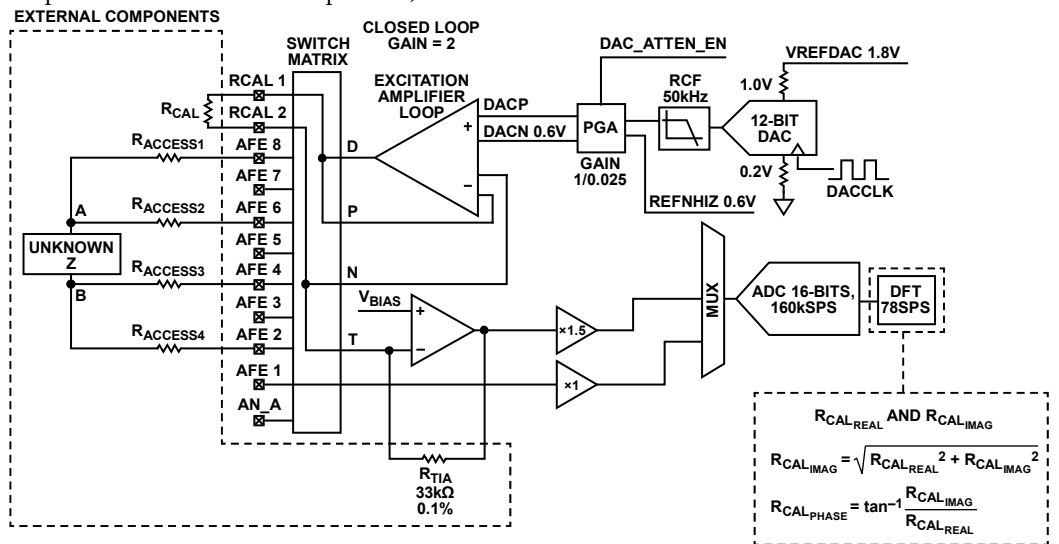


Figure 2. 4-Wire Topology for ADuCM350—Measuring R_{CAL}

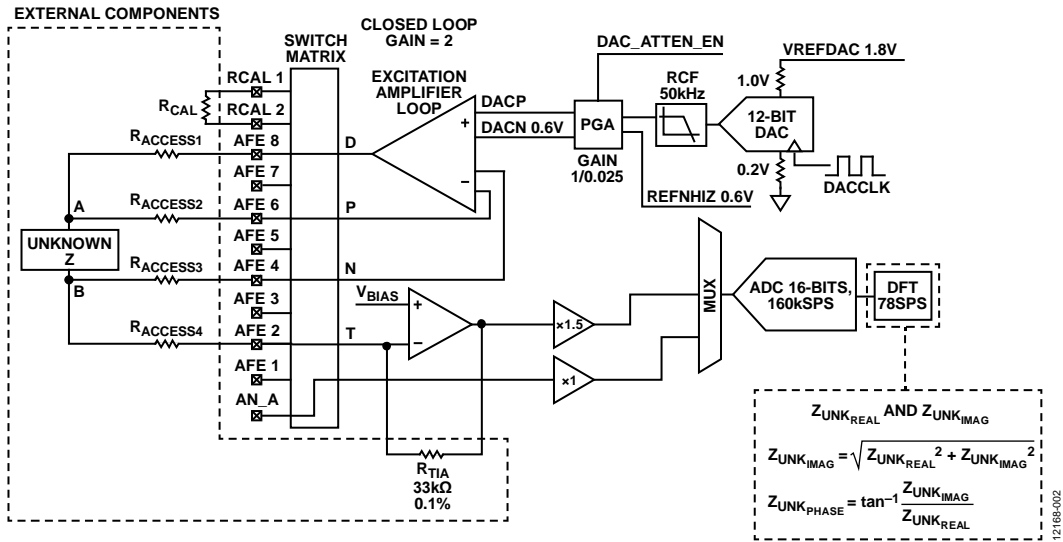


Figure 3. 4-Wire Topology for ADuCM350—Measuring Impedance (Z)

THE 4-WIRE BIOISOLATED METHOD

BASIC 4-WIRE THEORY

In a classic 4-wire/4-terminal sensing system, a differential current source is used to force a known current into the sensor. This forced current generates a potential difference across the Unknown Z, which is measured according to Ohm's law where:

$$V = I \times R$$

When the current is forced, the access wires to Z also lead to a drop in voltage, which causes inaccuracies in measurement. To remove this loss from the actual measurement of Z, a differential pair of sense lines are connected to Z at Point A and Point B as shown in Figure 2.

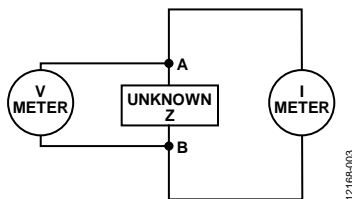


Figure 4. Basic 4-Wire Topology

The differential sense lines are designed with high input impedance stages so that no current flows through the lines and there is no voltage drop across the lines. The impedance, Z, is then measured using the following equation:

$$Z = V_{METER}/I_{AC}$$

where:

V_{METER} is the voltage across Z or the sensor

I_{AC} is the ac current through Z or the sensor

4-WIRE BIOISOLATED THEORY IN APPLICATION

An alternative approach is to use a high precision excitation voltage source as the force signal. Apply this voltage to Z and measure the response current using a high accuracy current meter (see Figure 3). The unknown impedance, Z, is then measured by the following equation:

$$Z = V_{METER}/I_{METER}$$

where:

I_{METER} is the current through the sensor.

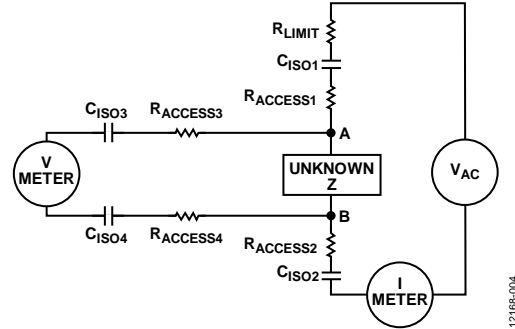


Figure 5. 4-Wire Bioisolated Topology

Referring back to Figure 3, it is possible to measure 4-wire impedance using the [ADuCM350](#). The excitation stage excites the sensor with a known voltage, which is accurately differentially sensed using the internal instrumentation loop. The current response is measured through the TIA channel and converted to a voltage.

In a real-world application, such as those governed by the IEC 60601 standards, the Z (or sensor) allows a limited dc voltage across Z or the sensor. The restrictions on the ac current forced on the sensor are more relaxed. The ac voltage source is selected for the force connection to the sensor to utilize the [ADuCM350](#) DFT capability.

In Figure 5, C_{ISO1} and C_{ISO2} are discrete isolation capacitors that ensure that no dc voltage appears across the sensor. $R_{ACCESS1}$ and $R_{ACCESS2}$ are access or lead resistance inherent in the connections to the sensor. R_{LIMIT} is an extra level of security to guarantee the maximum allowable excitation current seen by the sensor in a scenario where the R_{ACCESS} resistance is removed from the measurement.

A 4-WIRE BIOISOLATED SOLUTION

Referring to Figure 5, the following is required:

- A precision ac voltage source
- A high precision current meter
- A precision differential voltage meter

Precision AC Voltage Source

The ADuCM350 has a high precision excitation control loop, which drives a precision ac voltage to the sensor. An internal differential sense configuration guarantees the accuracy of the voltage source (see Figure 6). The positive sense, P, is tied to the drive terminal, D, in the configurable switch matrix. A direct digital synthesizer (DDS)-based sine wave generator is used to generate the ac stimulus through a 12-bit DAC. For more information regarding the transmit stage, refer to the [ADuCM350 Hardware Reference Manual](#).

High Precision Current Meter

The ADuCM350 utilizes a TIA amplifier for current to voltage conversion for measurement by the high precision ADC, the gain of which is set by an external resistor, R_{TIA} . The TIA channel sinks the sensor excitation current, and the channel is precisely biased on a common-mode voltage of 1.1 V. Significant analog and digital filtering is performed on measurement for rejection of interferers and noise. The T and N channels are tied together using the switch matrix for accurate sense capability on the current measured (see Figure 7).

The ADC converts the current measurement with a 160 kSPS ADC. A 2048 sample point DFT is performed on the data; resulting real and imaginary components for the current measurement are calculated.

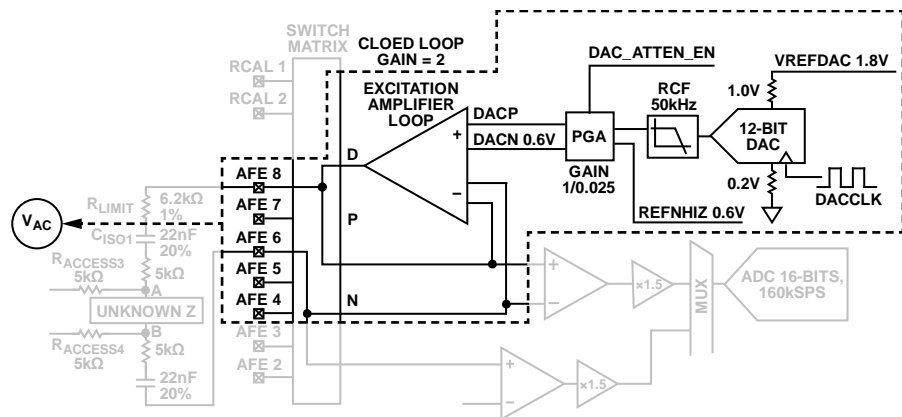


Figure 6. AC Voltage Source on the ADuCM350

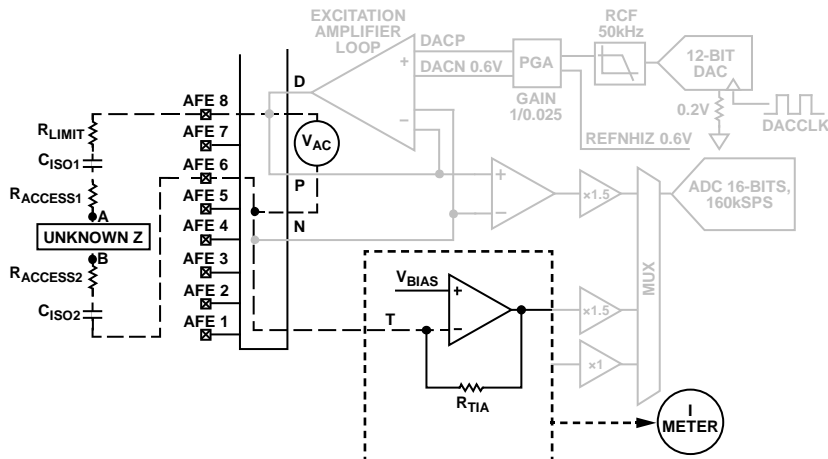


Figure 7. High Precision Current Meter

Precision Differential Voltage Meter

To differentially sense the voltage across the sensor, a low power in-amp with excellent noise and common-mode rejection is required (see Figure 8). The AD8226 is selected for this application. The AD8226 is referenced off the common mode of the system set by the V_{BIAS} voltage on the TIA channel. The output of the in-amp is fed back into the ADuCM350 through one of the auxiliary channels, for example, AN_A.

The ADC converts the auxiliary voltage measurement with a 160 kSPS ADC. A 2048 sample point DFT is performed on the data and resulting real and imaginary components for the voltage measurement are calculated.

4-WIRE, BIOISOLATED MEASUREMENT SYSTEM BLOCK DIAGRAM

Figure 9 shows the combination of the following:

- A precision ac voltage source (ADuCM350 excitation stage)
- A high precision current meter (ADuCM350 TIA channel stage)
- A precision differential voltage meter (AD8226 instrumentation amplifier)

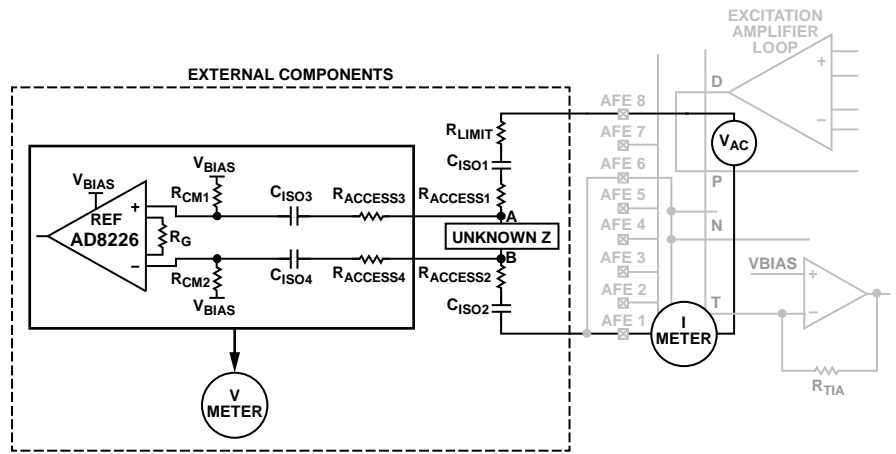


Figure 8. High Precision Differential Voltage Meter

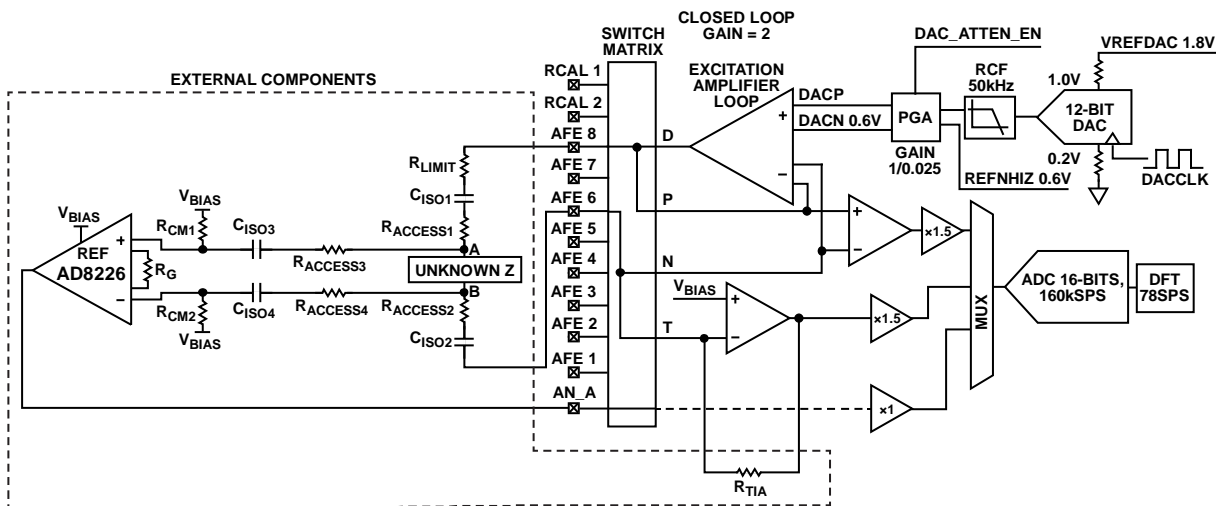


Figure 9. 4-Wire Measurement System Using the ADuCM350 and the In-Amp (AD8226)

HOW TO CALCULATE THE UNKNOWN Z

After obtaining the current and voltage DFT measurements, the device can exit the AFE sequencer and calculate the impedance of the sensor using the following equations:

$$\text{Voltage Measurement Magnitude} = \sqrt{(r^2 + i^2)}$$

$$\text{Voltage Measurement Phase} = ATan(i/r)$$

$$\text{Current Measurement Magnitude} = \sqrt{(r^2 + i^2)}$$

$$\text{Current Measurement Phase} = ATan(i/r)$$

where r and i are the real and imaginary components from the voltage and current DFT measurements, respectively.

To calculate the Impedance Z , use Ohm's law by dividing the voltage magnitude by the current magnitude while taking into account the gains of the signal chain as follows:

$$\begin{aligned} Z(\text{Magnitude}) = & \\ & (\text{Voltage Magnitude}/\text{Current Magnitude}) \times \\ & (1.5/1.494) \times R_{TIA} \end{aligned}$$

The current measurement value is converted to a voltage, using the R_{TIA} , for measurement purposes. This gain must be taken into account.

The 1.5 gain in the equation is the ratio between the gain of the [ADuCM350](#) current measurement channel, which is 1.5, vs. the gain of the [ADuCM350](#) voltage measurement channel, which is 1.

The gain of the in-amp is determined by the selection of R_G . For the [AD8226](#), this is determined by

$$R_G = (49.4 \text{ k}\Omega)/(G - 1)$$

By choosing $R_G = 100 \text{ k}\Omega$, the gain is 1.494.

Note that these equations are taken into account in the example provided in the [ADuCM350 Software Development Kit](#).

EXAMPLE OF A 4-WIRE BIOISOLATED SYSTEM SENSOR CONFIGURATION

In the example described in this application note, measure the impedance of an RC type sensor, with the configuration shown in Figure 10, for a 30 kHz excitation signal. Note that T_{OL} indicates tolerance.

The sensor details are as follows:

- $C_S = 220 \text{ pF}$
- $R_S = 20 \text{ k}\Omega$
- $R_P = 100 \text{ k}\Omega$

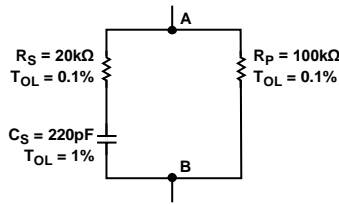


Figure 10. RC Sensor to be Measured

The total impedance of the sensor must be calculated to verify the system accuracy.

1. Calculate the complex sum of

$$R_S + C_S = Z_S = 34962 \angle -55.11$$

2. Calculate $Z_S ||$ with

$$R_P = Z_T = 28337.15 \angle -41.66$$

which is the total impedance of the RC sensor to be measured.

4-WIRE BIOISOLATED NETWORK

For this 4-wire example, select the following components:

- A lead access resistor, $R_{ACCESSx} = 4.99 \text{ k}\Omega$
- An isolation capacitor, C_{ISOx} , of 47 nF

If Z is close to or less than $R_{ACCESSx}$, a potential divider effect occurs that limits the bandwidth of the [ADuCM350](#) thus degrading accuracy (see Figure 11).

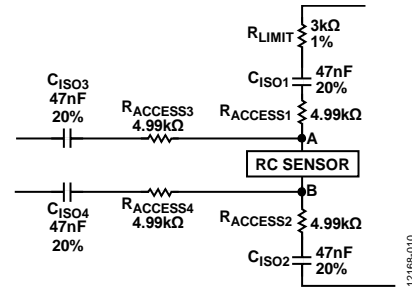


Figure 11. 4-Wire, Bioisolated Measurement Network

AFE OPTIMIZATION

Optimizing the **ADuCM350** consists of the following steps:

1. Calculate the R_{LIMIT} resistor.
2. Calculate R_{TIA} .
3. Calculate the R_G of the **AD8226**.
4. Calculate R_{CAL} .

CALCULATE THE R_{LIMIT} RESISTOR

When calculating the R_{LIMIT} resistor, note that the maximum output voltage from the **ADuCM350** = 600 mV peak.

The maximum allowed ac current at 30 kHz is the following:

$$300 \mu\text{A rms (Targeting IEC 60601)} = 424 \mu\text{A peak}$$

Being conservative, set the maximum allowable ac current to 200 μA peak (<50%).

$$R_{LIMIT} \approx 600 \text{ mV peak} / 200 \mu\text{A peak} = 3 \text{ k}\Omega$$

This calculation ignores C_{ISOX} due to its small size.

CALCULATE R_{TIA}

R_{TIA} is the feedback resistor on the TIA to convert the current to a voltage.

Minimum impedance/maximum current seen by the TIA is

$$Z_{PNMIN} = \sqrt{(\text{Real})^2 + (\text{Sum of imaginary})^2}$$

$$\sqrt{\left(R_{LIMIT} + R_{ACCESS1_{MIN}} + Z_{UNKNOWN_{MIN}} + R_{ACCESS2_{MIN}} \right)^2 + \left(X_{C_{ISO1_{MIN}}} + X_{C_{ISO2_{MIN}}} \right)^2}$$

Assume 20 k Ω is the minimum impedance of $Z_{UNKNOWN}$.

$$R_{ACCESS1} = R_{ACCESS2} = 4.99 \text{ k}\Omega$$

$$R_{LIMIT} = 3 \text{ k}\Omega$$

$$X_{C_{ISO1}} = X_{C_{ISO2}} = 289.37 \Omega$$

$$Z_{PNMIN} = 32.985 \text{ k}\Omega$$

Note the following:

- The maximum voltage swing is 600 mV peak.
- The highest signal current into TIA = 600 mV peak / 32.98 k Ω = 18.19 μA peak.
- The peak voltage at output of TIA (maximum allowed by the **ADuCM350**) = 750 mV peak.
- R_{TIA} resistor to give peak 750 mV voltage for peak signal current is $R_{TIA} = 750 \text{ mV} / 18.19 \mu\text{A}$ and $R_{TIA} = 41.2 \text{ k}\Omega$.
- To prevent overranging of the ADC, add a safety factor of 1.2, that is, the minimum impedance is 1.2 times less than the specified minimum impedance of 32.985 k Ω = 27 k Ω .
- The R_{TIA} with a safety factor included = 41.2 k Ω / 1.2 and $R_{TIA} = 34.3 \text{ k}\Omega$.

Note that 33 k Ω is used for this example.

CALCULATE R_G OF THE **AD8226**

The maximum impedance of the sensor is the following:

$$Z_{UNKNOWN_{MAX}} = 28.337 \text{ k}\Omega$$

A safety factor is incorporated on the R_{TIA} to prevent the ADC from overranging. The same must be done here thus the maximum peak current is divided across differential inputs of **AD8226** by a factor of 1.2.

$$\text{Peak Current Seen at } V_{IN} \text{ (AD8226)} =$$

$$(18.19 \mu\text{A peak}) / 1.2 = 15.16 \mu\text{A peak}$$

$$V_{IN} \text{ (AD8226)} =$$

$$15.16 \mu\text{A peak} \times 28.337 \text{ k}\Omega = 439.6 \text{ mV peak}$$

$$AD8226 G = 750 \text{ mV peak} / (439.6 \text{ mV peak}) = 1.706$$

If a further safety factor of 1.1 is used on the peak-to-peak of the voltage (this may be unnecessary for the application), then

$$AD8226 G = 750 \text{ mV peak} / (1.1 \times 439.6 \text{ mV peak}) = 1.55$$

$$AD8226 G = 1 + (49.4 \text{ k}\Omega / R_G) = 1.55$$

$$R_G = (49.4 \text{ k}\Omega) / (1.55 - 1) = 89.8 \text{ k}\Omega$$

Select an R_G of 100 k Ω because it is a standard value.

$$AD8226G = 1 + (49.4 \text{ k}\Omega / R_G) =$$

$$1 + (49.4 \text{ k}\Omega / 100 \text{ k}\Omega) = 1.494$$

Note that the **AD8226** has bandwidth limitations. For a frequency of 50 kHz, the gain is limited to 10 (see Figure 12).

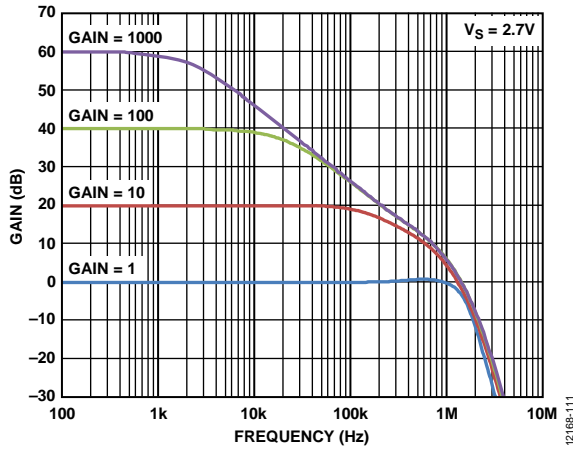


Figure 12. Gain vs. Frequency of [AD8226](#) at 2.7V

CALCULATE R_{CAL}

The calibration of the auxiliary channel and the TIA channel must take into account the gain through the system.

For the voltage measurement channel, the auxiliary channel is calibrated.

For the current measurement channel, the temperature sensor is calibrated, and the results are loaded to the offset and gain registers of the TIA channel. This calibration and loading ensures that the difference between the voltage and current gain is exactly 1.5.

The calibration of the auxiliary channel and the TIA channel is done for the user in the 4-wire bioisolated example code in the [ADuCM350 Software Development Kit](#).

4-WIRE BIOISOLATED MEASUREMENTS

HARDWARE SETUP FOR 4-WIRE BIOCONFIGURATON BOARD

When setting up the [EVAL-ADuCM350EBZ](#) motherboard, do the following:

- For the voltage measurement, insert LK1 (Auxiliary Channel A).
- Open LK6.

For the [ADuCM350](#) 4-wire bioconfiguration board, do the following:

- Insert LK7, LK8, LK9, and LK10.
- Insert LK16, LK17, LK18, and LK19 in Position A to measure an external sensor. In this example, the network shown in Figure 10 and Figure 11 is measured. The result appears as shown in Figure 13.

Firmware Example

Code available in the ADuCM350 Software Development Kit is designed to be used with the 4-wire bioconfiguration board to validate the solution discussed in this application note.

The [Readme.txt](#) in the example folder provides more details on the measurement.

After downloading the ADuCM350 Software Development Kit, go to `C:\Analog Devices\ADuCM350BBCZ\EVAL-ADUCM350EBZ\examples`.

1. Click the `BioImpedanceMeasurement_4Wire` folder.
2. Click the `.eww` file in IAR.
3. During the download and debug stage, open the **Terminal** I/O window to read the returned results.

Measurement Results

Impedance Magnitude

Measured Result = 28405 Ω

Theoretical Value Measured $Z_T = 28337 \Omega$

However, the C_s of 220 pF used in the calculation had a tolerance of 1%.

Upon analysis, the capacitor measured closer to 221 pF.

In theory, a C_s of 221 pF gives a Z_T of 28416 Ω vs. the measured result of 28405 Ω.

For more details, refer to the Sensor Configuration section.

Impedance Phase

The current 4-wire bioisolated configuration is not capable of measuring accurate phase measurements.

If an absolute phase measurement is required, use a single chip [ADuCM350](#) 4-wire measurement configuration. Note that this configuration does not have isolation capacitors (C_{ISOX}).

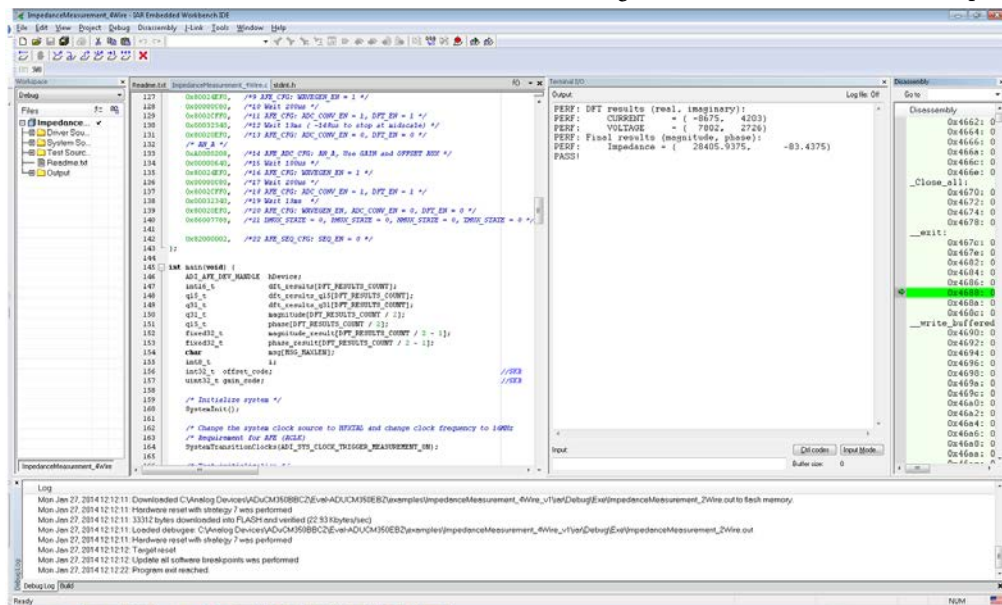


Figure 13. 4-Wire Measurement Display on Terminal Input/Output

SCHEMATICS FOR THE 4-WIRE BIOCONFIGURATION (BIO3Z) BOARD

MOTHERBOARD CONNECTOR - ALIGN J8 AND J9.

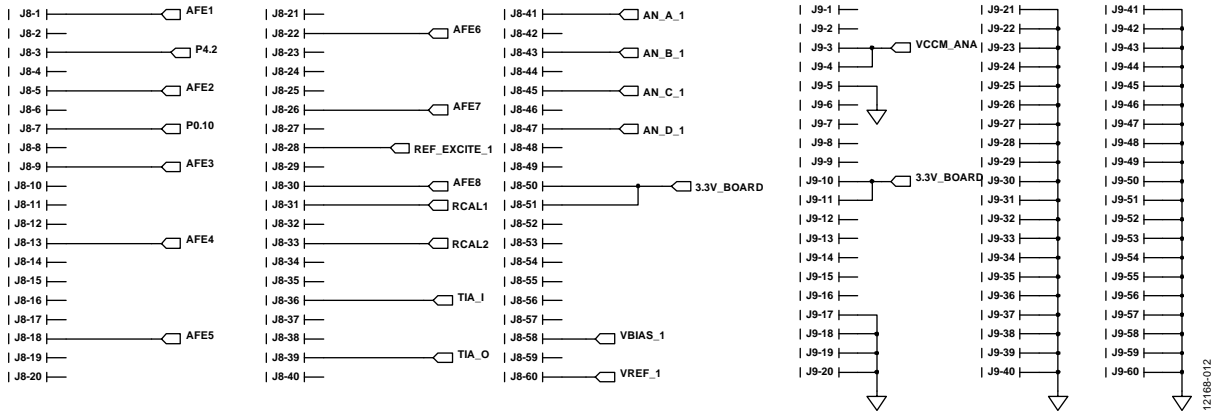
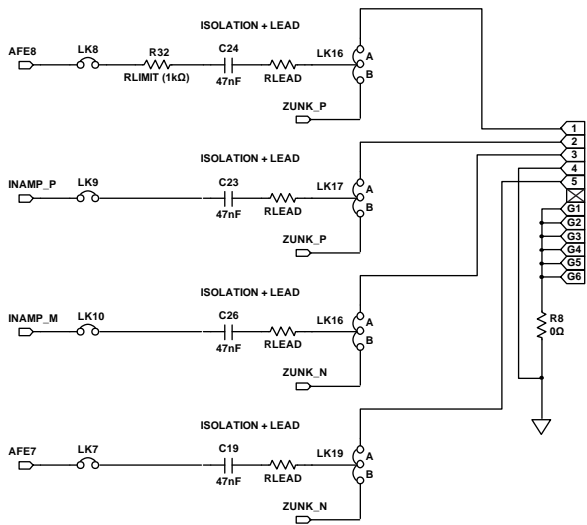


Figure 14. Motherboard Connector

4-WIRE BIO IMPEDANCE CONFIGURATION



UNCOMMITTED CONFIGURATION

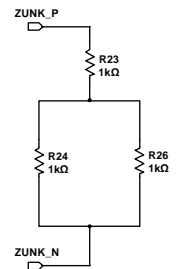
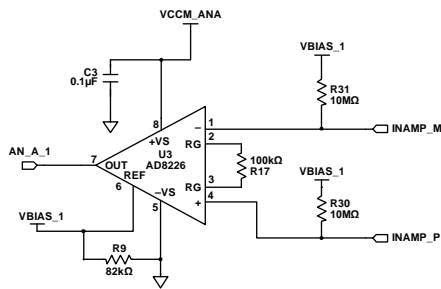
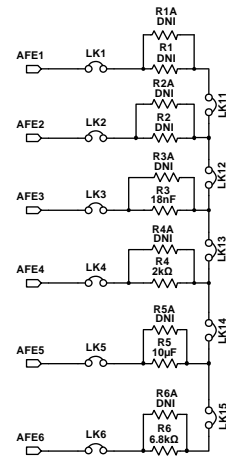


Figure 15. 4-Wire and Uncommitted Schematics

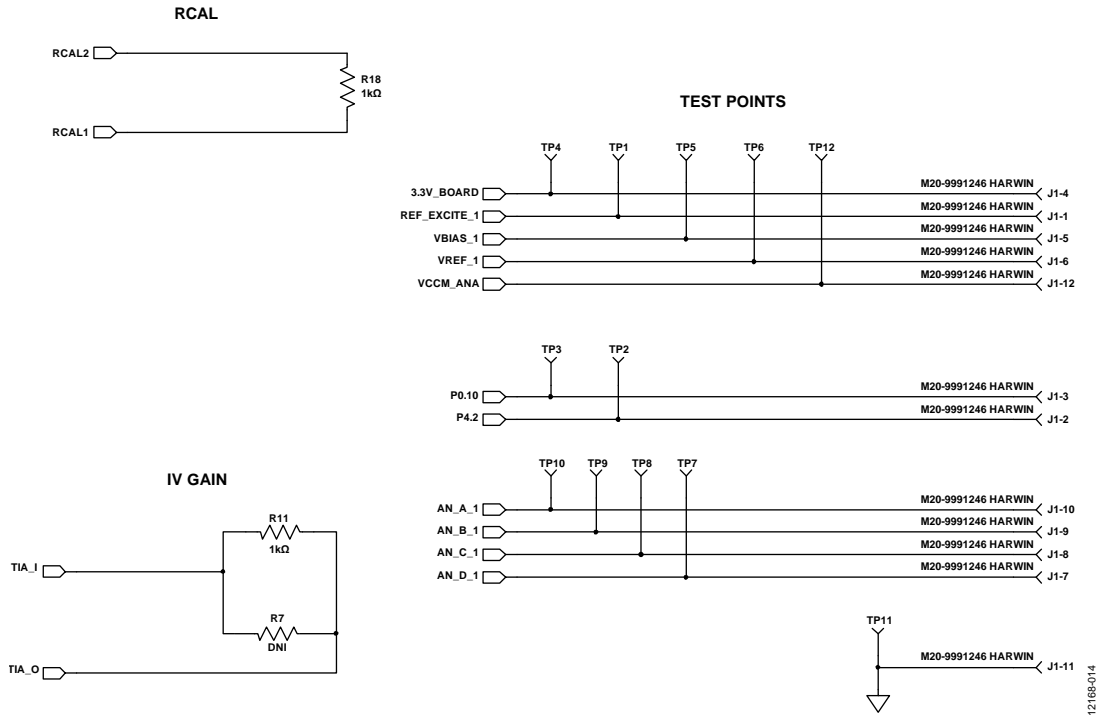


Figure 16. Miscellaneous Schematics

LIMITATIONS ON USE AND LIABILITY

The application described in this application note is specific to the [ADuCM350](#) for use with the [EVAL-ADuCM350EBZ](#) evaluation board. In addition to the terms of use contained in the evaluation board user guides, it is understood and agreed to that the evaluation board or design must not be used for diagnostic purposes and must not be connected to a human being or animal. This evaluation board is provided for evaluation and development purposes only. It is not intended for use or as

part of an end product. Any use of the evaluation board or design in such applications is at your own risk and you shall fully indemnify Analog Devices, Inc., its subsidiaries, employees, directors, officers, servants and agents for all liability and expenses arising from such unauthorized usage. You are solely responsible for compliance with all legal and regulatory requirements connected to such use.