One Technology Way • P.O. Box 9106 • Norwood, MA 02062-9106, U.S.A. • Tel: 781.329.4700 • Fax: 781.461.3113 • www.analog.com

AN-1557
APPLICATION NOTE

Implementing the AD5940 and AD8233 in a Full Bioelectric System

by Micheál Lambe

INTRODUCTION

The AD5940 is a high precision, ultra-low power, Analog Front End (AFE) system designed to excite and measure a sensors current, voltage or impedance response.

The AD5940 features two high precision measurement loops. An ultra low power, sub 1 kHz loop and a high speed, sub 200 kHz loop allow the AD5940 to precisely measure the impedance of a sensor.

The AN-1557 details how to set up the AD5940 and the AD8233 in a full bioelectric system that can perform electrodermal activity (EDA), body impedance analysis (BIA), and electrocardiogram (ECG) measurements through the same set of electrodes.

The hardware used is the AD5940 evaluation kit which includes the EVAL-ADICUP3029 ARM based, Arduino form factor microcontroller, the EVAL-AD5940ARDZ evaluation board, and the bioelectric daughter card shown in Figure 1.

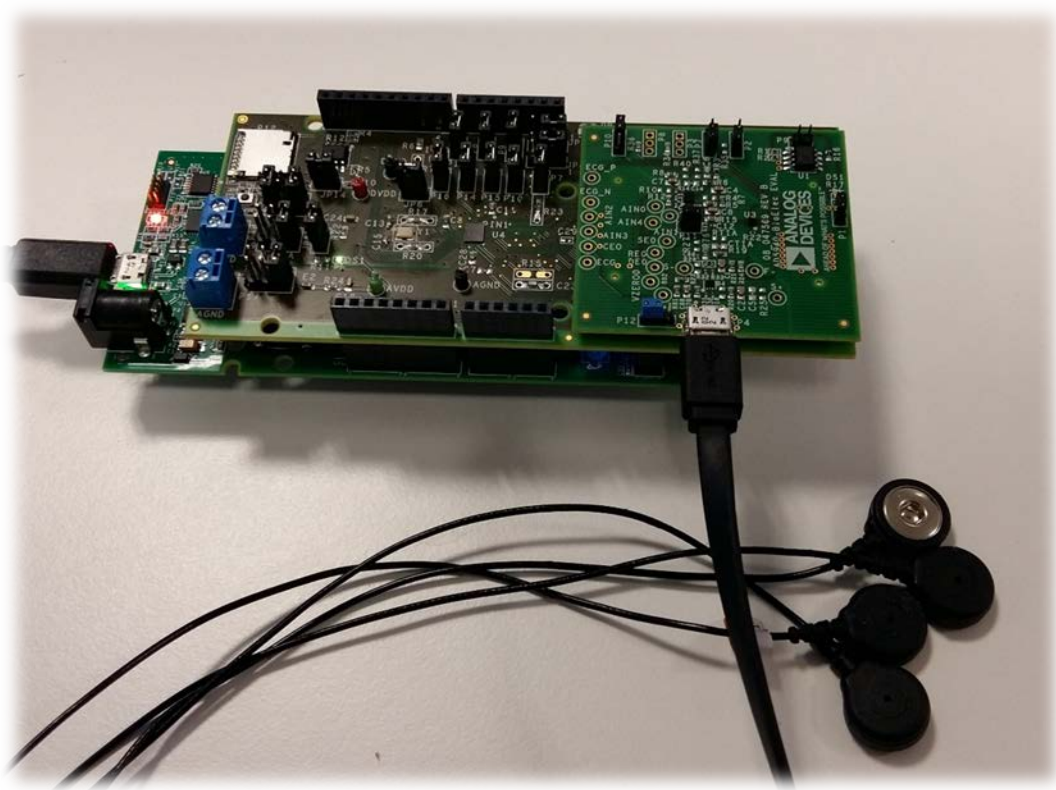

Figure 1. Hardware Setup

TABLE OF CONTENTS

REVISION HISTORY

5/2018—Revision 0: Initial Version

EVALUATION KIT

EVALUATION KIT CONTENTS

- EVAL-ADICUP3029
- EVAL-AD5940ARDZ
- AD5940 Bioelectric
- AD5940 Z Test
- ECG cable
- Micro USB to USB cable

EVAL-ADICUP3029

The EVAL-ADICUP3029 is the main mother board for the kit. This board has the ADuCM3029 microcontroller on board. This is one of ADI's leading edge Cortex M3 devices. It is used to communicate to the AD5940 via the Serial Peripheral Interface (SPI).

EVAL-AD5940ARDZ

This board contains the AD5940 device. It is an Arduino form factor board that plugs down onto the EVAL-ADICUP3029 board. There is an interface connector to connect different daughter cards onto it.

AD5940 Bioelectric

The AD5940 Bioelectric board contains the AD8233 chip used for ECG measurements. It contains the necessary discrete components required for ECG, EDA and BIA measurements. These include isolation capacitors and current limiting resistors. There is also an interface to connect measurement cables and the AD5940 Z Test board.

AD5940 Z Test

The AD5940 Z Test board contains a network of resistors, capacitors and switches. This was designed specifically for testing and verifying measurements. It can be used to model a range of body and skin impedances. It plugs into the AD5940 Bioelectric board via the USB connector.

ECG Cables

The ECG cables that are supplied with the evaluation kit are provided as a means of connecting the hardware to a simulator. The following are the name and colour mapping for the supplied cables:

- E1 = F+ = RED
- E2 = S+ = GREEN
- E3 = S− = BLUE
- E4 = F− = BLACK

MEASUREMENT SYSTEM OVERVIEW

AD5940 OVERVIEW

The AD5940 data acquisition loop consists of a low bandwidth loop, a high bandwidth loop, a high precision analog-to-digital converter (ADC), and a programmable switch matrix.

The low bandwidth loop consists of a low power, dual-output digital-to-analog converter (DAC) that generates V_{ZERO} and V_{BIAS}, and a low power transimpedance amplifier (TIA) used to convert input currents to voltage.

The low bandwidth loop is used for low bandwidth signals where the frequency of the excitation signal is sub 200 Hz such as EDA measurements.

The high bandwidth loop consists of a high speed DAC designed to generate a high frequency, ac excitation signal when making impedance measurements. The high bandwidth loop consists of a high speed TIA designed to convert high bandwidth current signals up to 200 kHz into voltages measured by the ADC.

The high bandwidth loop is used for body impedance measurements where the excitation frequency is in the range of 50 kHz.

The switch matrix is a series of programmable switches that allows the connection of external pins to the high speed DAC excitation amplifier and to the high speed TIA inverting input.

The switch matrix provides an interface to connect an external calibration resistor to the measurement system. It also provides flexibility for connecting electrodes.

AD5940 BIOELECTRIC SYSTEM

This application note describes how the AD5940 can be used in a bioelectric system with the AD8233. The three measurements in the system are EDA, BIA, and ECG.

The SensorPal GUI section describes how to use the Analog Devices, Inc., SensorPal graphic user interface (GUI) to configure, take, and display measurements.

2-WIRE BIO-IMPEDANCE

BIO-IMPEDANCE MEASUREMENT THEORY

The AD5940 can be configured for taking 2-wire bio impedance measurements. This is a relative accurate measurement and can be used for general-purpose impedance measurements on the body or for measuring internal body tissues etc.

2-wire bio-impedance is a voltammetry measurement. To measure an unknown impedance, an AC excitation signal is applied across the unknown impedance. The voltage of the excitation signal is measured. Then the current flow through the unknown impedance is measured. The current is converted to a voltage to be measured by the ADC via the trans-impedance amplifier. A DFT is performed on the ADC data for the current and voltage values. Using the real and imaginary parts, the magnitude is calculated to give $V_{Zunknown}$ and $I_{Zunknown}$.

The following equation is used to calculate the unknown impedance magnitude of the sensor:

$$|Z_{UNKNOWN}| = \frac{|V_{Z_{UNKNOWN}} MAG|}{|I_{Z_{UNKNOWN}} MAG|} \times R_{TIA}$$

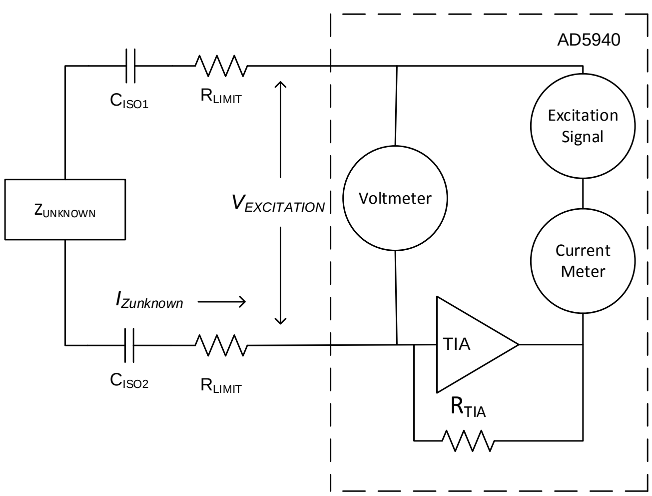

Figure 2. 2-Wire Bio-Impedance Measurement Diagram

Because this is a bio-impedance measurement it must conform to IEC60601 standard which sets guidelines for max allowable current that can enter the human body. R_{LIMIT} limit the current and C_{ISO} are isolation capacitors which guarantee that no DC current enters the body. Guidelines for selecting the correct values can be found in the Calculations section below.

BIO-IMPEDANCE SOLUTION USING THE AD5940

The following section describes the blocks of the AD5940 used to perform 2-wire BIOZ measurements. As outlined above, a 2-wire BIOZ measurement requires an AC voltage source, a voltage measurement channel and a current measurement channel. Each of these block is described below.

For 2-wire BIOZ, the impedance under test can be connected between CE0 and any one of the following: SE0, DE0, AINx.For the purposes of this application note the unknown Z is connected between CE0 and AIN1.

Excitation Signal

The AD5940 uses its waveform generator, high speed DAC, (HSDAC) and excitation amplifier to generate high frequency excitation signals. The frequency is programmable from DC up to 200kHz. The signal is applied to the sensor through the CE0 pin as shown in Figure 3. The signal amplitude is programmable up to ±607mV.

Measuring Voltage

The voltage of the excitation signal is measured as it is being applied to the sensor. The positive input to the ADC is the P node which is connected to CE0 via the switch matrix as shown in Figure 3. The negative input to the ADC is the N node which is connected to the negative input of the high speed TIA. Using the DFT hardware accelerator, a DFT is performed on the ADC data where the real and imaginary parts are calculated and stored in the data FIFO.

Measuring $Z_{UNKNOWN}$ Current

To measure the $Z_{UNKNOWN}$ current, the same excitation signal is applied to the sensor. This time the HSTIA converts the current to a voltage to be read by the ADC via the gain resistor, $R_{TIA.}$ Similarly, a DFT is performed on the ADC results and the real and imaginary parts are stored in the data FIFO to be read by the host microcontroller.

Calculating Z_{UKNOWN}

The AD5940 uses the sequencer to store commands. A host microcontroller (in this case, the ADICUP3029) writes the required commands to the sequencer. These commands set up the DAC, ADC, and TIA for measurements. The sequencer executes the commands automatically, independent of the microcontroller. The voltage measurement is performed first. An interrupt is generated when the data FIFO is full. The microcontroller then reads the FIFO and stores the real and imaginary DFT results. The ADC mux is then configured to connect the HSTIA output to the ADC to measure current. The sequence is run again, and the AD5940 generates an interrupt when the data FIFO is full, which alerts the host controller to read the data.

Use the following equations to determine $Z_{UNKNOWN}$:

$$|V_{MAG}| = \sqrt{r^2 + i^2}$$

$$|I_{Z_{UNKNOWN}} MAG| = \sqrt{r^2 + i^2}$$

$$|Z_{UNKNWON}| = \frac{|V_{MAG}|}{|I_{Z_{UNKNOWN\ MAG}}|} \times R_{TIA}$$

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

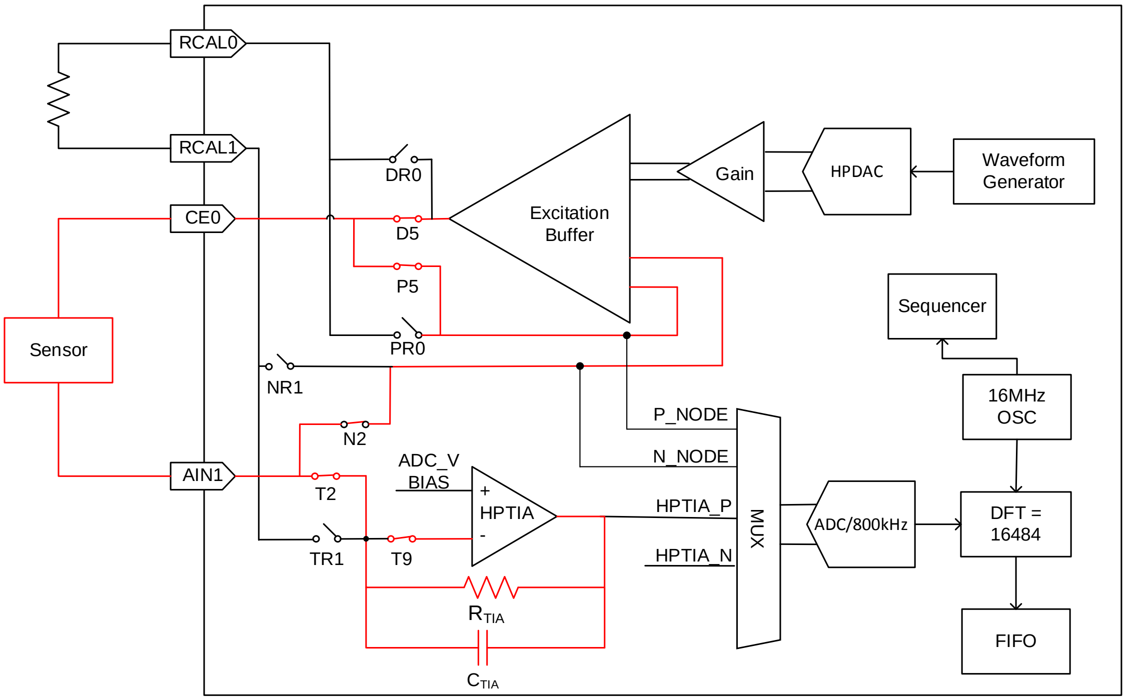

Figure 3: 2-Wire BIOZ Block Diagram

CALCULATIONS

To optimize the AD5940 for 2-wire BIOZ measurements a number of calculations need to be made. The following components must be considered:

- R_{LIMIT}
- Isolation capacitors
- R_{TIA}
- R_{CAL}

Calculating R_{LIMIT}

This calculation is described in Current Limit Resistor section under the BIA chapter.

Isolation Capacitors

This section is described in Isolation Capacitors section under the BIA chapter. However, the hardware that accompanies this application note was designed to carry out EDA and BIA measurements on the same electrodes.

Calculating R_{TIA}

To calculate R_{TIA}, the gain resistor for the HSTIA, first calculate the minimum impedance/maximum current seen by the HSTIA:

$$Z_{MIN}= \sqrt{(Real)^2 + (Sum of Imaginary)^2}$$

$$= \sqrt{\begin{matrix}(R_{LIMIT} + R_{ACCESS1_{MIN}} + Z_{UNKNOWN_{MIN}} + R_{ACCESS2_{MIN}})^2 \\ +(XC_{ISO1_{MIN}} + XC_{ISO2_{MIN}})^2\end{matrix}}$$

($R_{ACCESS1}$ and $R_{ACCESS2}$ represent resistances in leads connecting the sensor. For calculating Z_{MIN} they are assumed 0 Ω)

Assume Z_{UKNOWN} = 200 Ω.

XC_{ISO1} = XC_{ISO2} = 67.73 Ω @ 50 kHz.

Solving the equation gives Z_{MIN} = 1.2 kΩ.

Note the following:

Maximum voltage is 600 mVpeak.
Max current into TIA = 600mV/Z_{MIN} = 500 µA.
Peak voltage at output of TIA = 900 mVpeak so it is within the ADC range.
Thus, R_{TIA} = 900 mVpeak/500 µA peak = 1.8 k Ω. There is no 1.8 k Ω. R_{TIA} option on the AD5940, so the 1 k Ω option is selected

Selecting R_{CAL}

R_{CAL} is a precision resistor used in conjunction with the HSDAC and excitation amplifier to generate accurate currents. It is used to calibrate the HSTIA gain resistor. Optimally, R_{CAL} should be selected so that is close to the value of R_{TIA}. In this case R_{CAL} should be 1kΩ. To guarantee accuracy it should have a 0.1% tolerance.

CALCULATING UNKNOWN Z

The AD5940 uses the sequencer to store commands. A host microcontroller writes the required commands into command memory, and the AD5940 executes the commands automatically. The first measurement that is taken is the voltage measurement. This is only needed once and the voltage measurement result is stored. The sequencer then runs the measurement sequence which applies the excitation voltage and measures the response current performing a DFT on the data. The real and imaginary parts are stored in the FIFO. The sequencer can be configured to run periodically using the sleep/wakeup timer.

The host microcontroller reads the data FIFO to get the real and imaginary results for the current measurement. Using these values and the real and imaginary voltage results calculated earlier the following equations are used:

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

$$Voltage\ Measurement\ Phase = tan^{-1} i/r$$

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

$$Current\ Measurement\ Phase = tan^{-1} i/r$$

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

To calculate the impedance Z, use Ohm's law by dividing the voltage magnitude by the current magnitude. Convert the current measurement value into a voltage using R_{TIA}. This gain needs to be taken into account. Therefore, the equation to determine the unknown impedance is:

$$|Z| = \frac{Voltage\ Magnitude}{Current\ Magnitude} \times R_{TIA}$$

TAKING 2-WIRE BIOZ MEASUREMENTS

Hardware Setup

The EVAL-ADICUP3029, EVAL-AD5940ARDZ and AD5940 bioelectric evaluation board and the AD5940 Z Test boards are required to perform 2-wire BIOZ measurements. Stack the boards as per Figure 16.

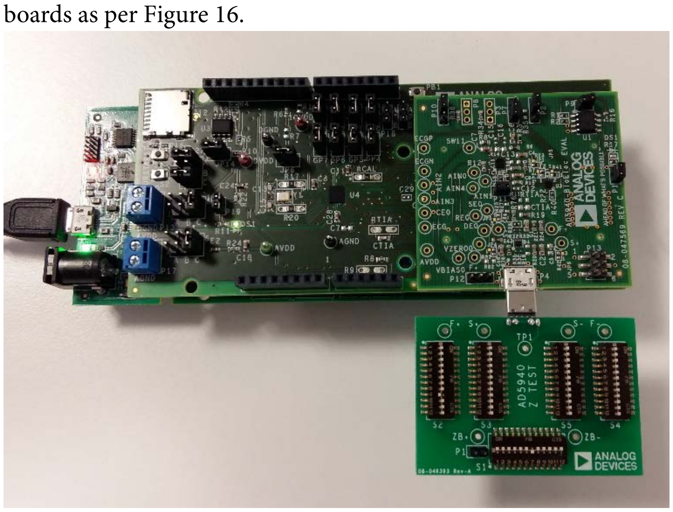

Figure 4: Hardware with Impedance test board

The jumpers on the AD5940-BioElect board do not have any impact on the 2-wire BIOZ measurements so can remain in the default position.

On the AD5940 Z Test board there are 5 banks of switches labelled S1 – S5. Banks S2, and S4 are used to simulate contact and lead impedances. S1 is used to simulate bio impedance. S3 and S5 are not applicable to 2-wire BIOZ. To test measurement accuracy set all switches on S2 and S4 to "ON" position. This sets the contact and lead impedance to zero. Open switch 9 on bank S1 to set the unknown impedance value to 2kΩ as shown in **Error! Reference source not found.**.

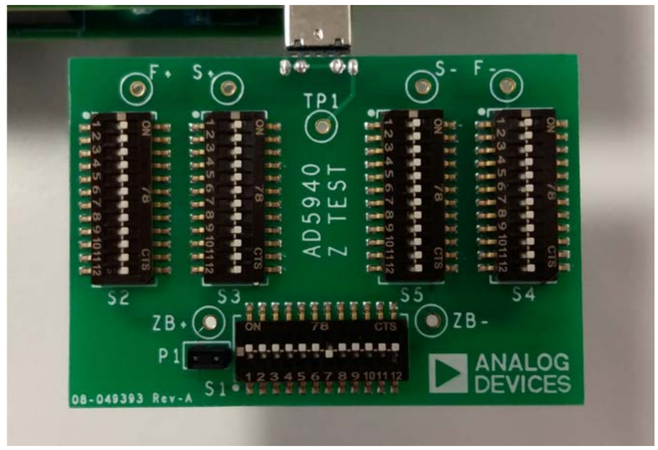

Figure 5: Impedance Test Board

Firmware Setup

To use the AD5940 for BIA measurements, use the SensorPal GUI. Refer to the SensorPal GUI section for setup instructions.

Alternatively, there is sample firmware that takes 2-wire BIOZ measurements. To run the firmware, IAR Systems Version 8.2.0 or later is required. Refer to UG-1292 for details on installation.

Navigate to the **Examples** folder in the software development kit and open the **AD5940_BIOZ-2WIRE** folder. Open the **ADICUP3029** folder and then the **ADICUP3029.eww** file to open the project workspace in IAR Embedded Workbench.

Compile and build the project. Start the debugger to begin code execution. Open a terminal program such as RealTerm and configure the baud rate to 230400. Select the COM port that the ADICUP3029 is connected to. The measurement results are streamed over a UART and can be saved to a file for analysis etc.

To modify the default application parameters, use the **AD5940BIOZStructInit(void)** function. The data structure **AppBIOZCfg_Type** contains the configurable parameters for the application. For more details on the firmware, refer to AD5940_Library_and_examples.chm file. This is located in the doc folder in the software development kit.

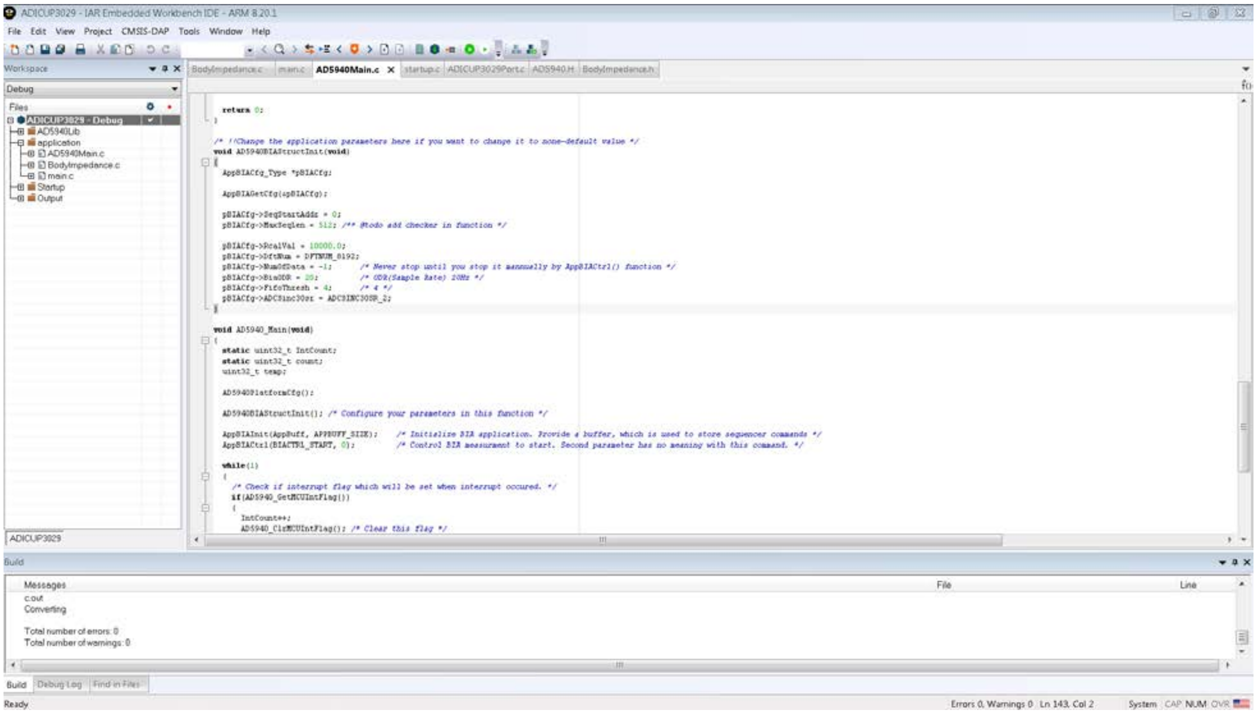

Figure 6. BIA Project in IAR

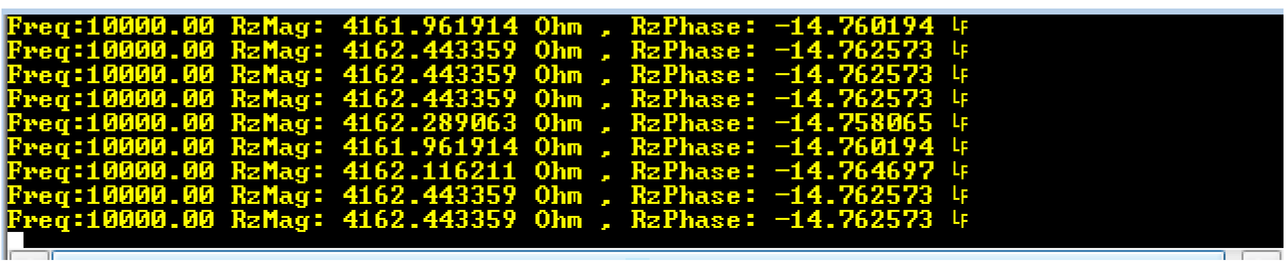

Figure 7. Results Displayed in Terminal

Measurement Results

The results displayed on the terminal are shown in Figure 7. Note how the magnitude is roughly 4162Ω. This is because the 2-wire BIOZ measurement measures the following:

- impedance under test +
- the contact impedance +
- the current limiting resistors +
- The isolation capacitors

Referring to Figure 8,

$$RzMag = R_{LIMIT1} + X_{CISO1} + R_{EC1} + R1||R2 + X_{C1} + R_{EC1} + X_{CISO2} + R_{LIMIT2}$$

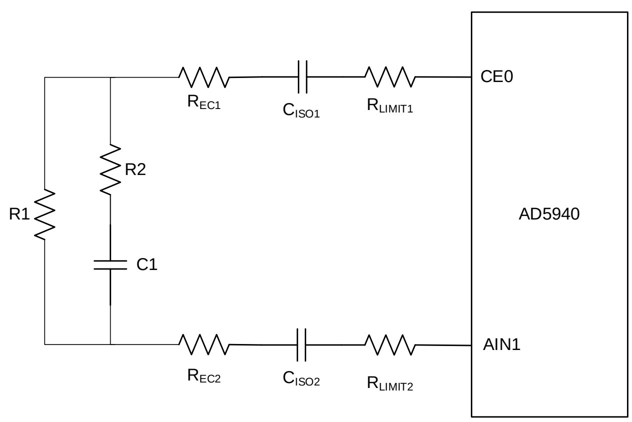

Figure 8: Circuit with Limiting Resistor and Isolation Capacitors

The *Impedance Profiling_2wireIEC.xls* workbook provides equations for calculating expected results taking into account the limiting resistors, isolation capacitors and contact impedances.

On the AD5940_BioElectric evaluation board R_{LIMIT1} and R_{LIMIT2} are both 1kΩ, C_{ISO1} is 15nF and C_{ISO2} is 470nF. Assume contact impedance, R_{EC1} and R_{EC2} is 0. Plugging these values into the workbook as in Figure 9, the theoretical values match closely with the measured values. The small error is down to the tolerances of the components.

User Input	Value	Default on Bio-Electric
Frequency	10000	
C_ISO1	1.50E-08	1.50E-08
R_Limit	1.00E+03	1.00E+03
R_EC1	0	0
R1	2.00E+03	
R2	1.00E+10	
C1	1.00E+04	
R_EC2	1000	0
C_ISO2	4.70E-07	4.70E-07
	Magnitude	Phase
Z_{TOTAL} =	4147.142801	-0.267179495
Z_{TOTAL} =	4147.142801	-15.30825742

Figure 9: Impedance Profiling_2wireIEC.xls workbook

ECG

ECG MEASUREMENT THEORY

An ECG measures how the electrical activity of the heart changes over time as action potentials propagate throughout the heart during each cardiac cycle. An ECG does not directly measure the cellular depolarization and repolarization within the heart, but rather the relative, cumulative magnitude of populations of cells eliciting changes in their membrane potentials at a given point in time. An ECG shows electrical differences across the heart when depolarization and repolarization of these atrial and ventricular cells occur.

Typically, the ECG is performed by placing two electrodes directly on the skin and reading the potential difference between the electrodes. This method is possible because these signals are transmitted throughout the body. The detected waveform features depend not only on the amount of cardiac tissue involved but also on the orientation of the electrodes with respect to the dipole in the heart. The ECG waveform looks slightly different when measured from different electrode positions, and typically an ECG is obtained using a number of different electrode locations (such as limb leads or precordial) or configurations (such as unipolar, bipolar, and modified bipolar).

For the purposes of an ECG, the human body can be considered a large volume conductor. The human body is filled with tissues surrounded by a conductive ionic fluid. The heart is suspended inside of that conductive medium. During the cardiac cycle, the heart contracts in response to action potentials moving along the chambers of the heart.

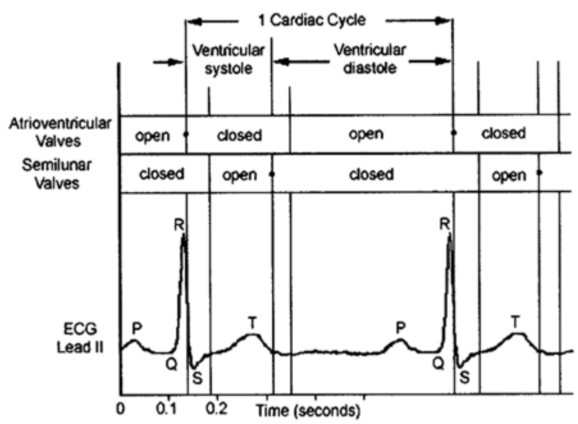

Figure 10. Typical Lead II ECG Waveform Compared to the Timing of Atrioventricular and Semilunar Valve Activity. This Figure Also Shows the Segments of the Cardiac Cycle During Which the Ventricles Are in Systole/Diastole.

ECG SOLUTION USING THE AD5940 AND AD8233

This section describes how to use the AD5940 and the AD8233 to take ECG measurements. Connect the four measurement electrodes to the switch matrix of the AD5940. In Figure 11, the signal chain for ECG measurements is highlighted. Connect Electrode E4 to the right leg drive (RLD) input of the AD8233 directly. Join E1 and E2 by closing internal switches on the AD5940 switch matrix and connecting to the AD8233 IN+ input via AFE2 by closing Switch P5 and Switch P6. Connect E3 to the AD8233 via AIN0 and AFE3 by closing Internal Switch N7 and Internal Switch N1. Connect the output of the AD8233 to Auxiliary Input AIN6 on the AD5940.

The AD5940 uses the sequencer to store measurement commands. A host microcontroller (in this case, the ADuCM3029) writes the required commands to the command memory. The sequencer runs the commands independent of the microcontroller. The initialisation sequence is ran first to configure the voltage references, the switch matrix, the ADC input source and the ADC filters. The measurement sequence runs periodically with a user defined sample frequency to sample ECG data from the AD8233 on the AIN6 pin.

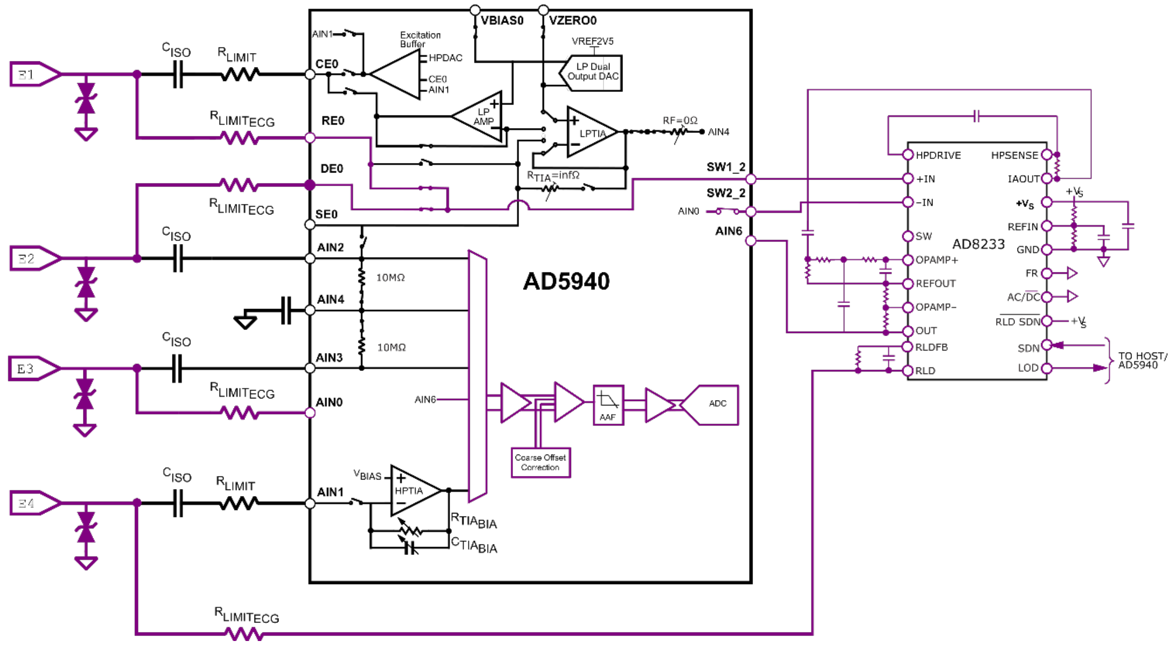

Figure 11. Block Diagram of AD5940 and AD8233

TAKING ECG MEASUREMENTS

Hardware Setup

The AD5940 bioelectric board included in the evaluation kit is ready to use (that is, no hardware modifications are required). There are a number of surface-mount resistors and capacitors connected to AD8233 pins that set the system bandwidth. On the AD5940 bioelectric board, the components were selected for sport bandwidth (7 Hz to 21 Hz) with a system gain of 767. To calculate the appropriate passive values for different cutoff frequencies, download the **AD8232_Filter_Design_Tool.zip** file found on www.analog.com.

This sport bandwidth is intended for nonclinical applications (for example a healthcare watch where ECG peaks are of interest). For applications where other artefacts of the ECG waveform are of interest monitor bandwidth is required.

The AD5940 evaluation kit is equipped with custom ECG cables. These cables can be used to connect to an ECG simulator for testing the hardware. Connect the right leg drive (RLD) electrode to F−. Connect the right hand (RH) to F+ and S+. Connect the left hand (LH) to S-.

Firmware Setup

To use the AD5940 and AD8233 for ECG measurements, use the SensorPal GUI. Refer to the SensorPal GUI section for setup instructions.

Alternatively, there is sample firmware that takes ECG measurements. To run the firmware, IAR Systems® Version 8.2.0 or later is required. Refer to UG-1291 for details on installation.

Navigate to the **Examples** folder in the software development kit and open the **AD5940_ECG** folder. Open the **ADICUP3029** folder and then the **ADICUP3029.eww** file to open the project workspace in IAR Embedded Workbench®.

Compile and build the project (for detailed steps on how to compile and build a projects refer to UG-1291). Start the debugger to begin code execution. Open a terminal program such as RealTerm and configure the baud rate to 230400. Select the communications port (COM port) that the EVAL-ADICUP3029 is connected to. The measurement results are streamed over a universal asynchronous receiver transmitter (UART) bus and can be saved to a file for analysis and to create graphs.

To modify default application parameters use the **AD5940ECGStructInit(void)** function. The data structure **AppECGCfg_Type** contains the configurable parameters. For more details on the firmware, refer to AD5940_Library_and_examples.chm file. This is located in the doc folder in the software development kit.

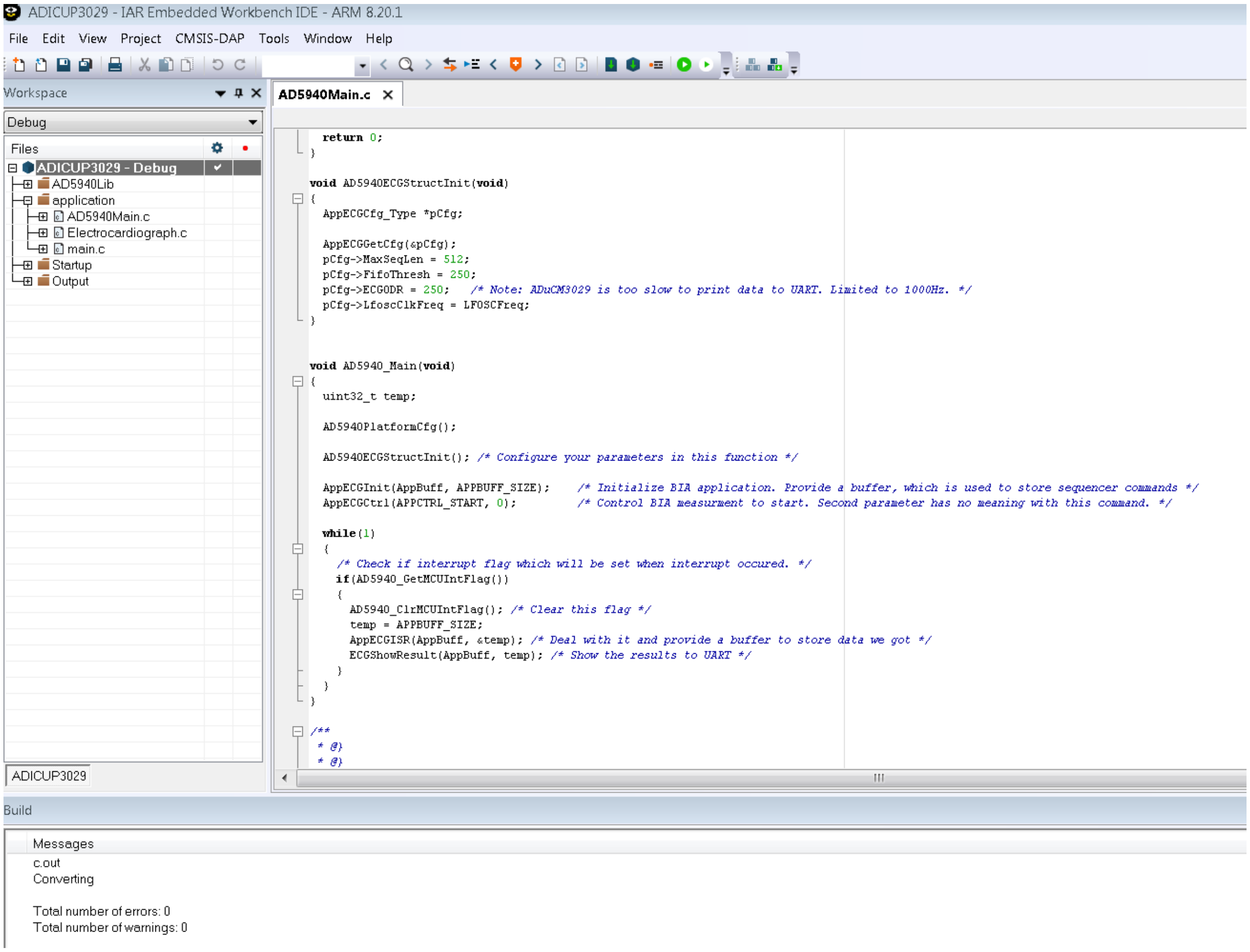

Figure 12. ECG Firmware in IAR Embedded Workbench

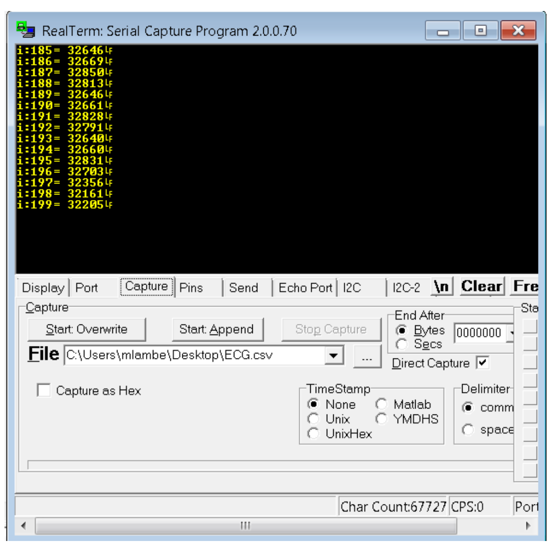

Figure 13. ECG ADC Results

BIA

4-WIRE BIOIMPEDANCE MEASUREMENT THEORY

The 4-wire BIA approach uses a high precision, ac voltage source to excite a sensor with a known voltage (V_{AC}). Simultaneously, a common-mode voltage is applied across the sensor. Measure the current (I) that flows from the unknown impedance and the voltage across the unknown impedance (V_M) to calculate the impedance.

Calculate the impedance using the following equation:

$$|Z| = V_M/I$$

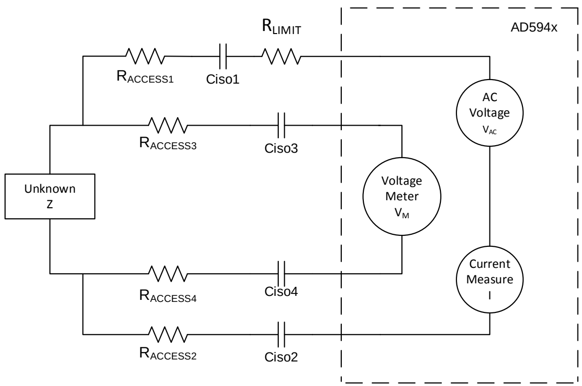

Figure 14. 4-Wire Bioimpedance Topology

In real-world applications, medical devices must conform to the IEC-60601 standard. This standard limits the amount of dc and ac voltage that can be applied to the body. In Figure 14, there are discrete isolation capacitors above C_{ISO1}, C_{ISO2}, C_{ISO3}, and C_{ISO4} that ensure no dc voltage appears across the body. R_{LIMIT} limits the current provided to the sensor to conform to the IEC-60601 standard. R_{ACCESS} represents the resistances of the electrodes connecting to the unknown impedance.

4-WIRE BIOIMPEDANCE SOLUTION USING THE AD5940

As outlined in the 4-Wire Bioimpedance Measurement Theory section, a 4-wire bioimpedance solution requires a precision ac voltage source, a high precision current meter, and a precision differential voltage meter.

The Precision AC Voltage Source section, the High Precision Current Meter section, and the Precision Differential Voltage Meter section describe how these are implemented on the AD5940.

Precision AC Voltage Source

The AD5940 uses a high speed DAC and waveform generator to generate the precision ac voltage. An internal differential sense configuration guarantees the accuracy of the voltage source by connecting CE0 and AIN1 back into the excitation buffer. Switch D5 in the programmable switch matrix connects the output of the excitation loop to the CE0 pin connected to the sensor. A sine wave generator generates a sine wave and outputs through the 12-bit, high speed DAC and excitation amplifier.

High Precision Current Meter

The AD5940 uses a high speed, high precision TIA for converting current from the sensor into a voltage measured by the ADC (See Figure 15). The TIA channel measures the response current and is precisely biased by ADC_VBIAS, which is 1.11 V. Tie the T channel and the N channel together using the switch matrix for accurate sense capability on the current measured. Figure 15 shows the connection between the sensor, the high speed TIA and ADC of the AD5940. The ADC converts the current measurement with an 800 kSPS speed. A discrete Fourier transform (DFT) is performed on the data. The DFT is implemented on the AD5940. The number of DFT points is configurable up to 16384. The AD5940 calculates the real and imaginary parts, and the host microcontroller easily calculates the unknown impedance of the sensor.

Precision Differential Voltage Meter

The AD5940 uses a low power DAC and a low power TIA to set the common-mode voltage between AIN2 and AIN3 through the AIN4/LPF0 pin. Connect the V_{BIAS} output of the low power DAC to the LPTIA positive input. The LPDAC is configured to output a precise 1.1 V. Connect the internal R_{FILTER} resistor at the LPTIA output. Connect VCM to AIN4/LPF0, which has a capacitor to GND that creates a low pass filter.

CALCULATING DISCRETE COMPONENTS

There are a number of discrete components needed in the system to guarantee safety and accuracy. The following section describes the calculations used to select a suitable:

- Current Limit Resistor
- Isolation Capacitors
- Gain resistors for the HSTIA

Current Limit Resistor

To conform to IEC60601 standards, the amount of AC current entering the human body must be limited. The maximum allowable AC current at 50 kHz is 500 µA, at 60 kHz it is 600 µA etc.

When calculating the R_{LIMIT} resistor, note that the maximum output voltage from the AD5940 is 1.2Vpeak-peak.

= 0.4243 Vrms.

Being conservative, set the maximum allowable AC current 80% of max, = 400 µA rms.

R_{LIMIT} = 0.424 V rms/400 µA rms = 1060.66.

Thus, a 1 kΩ R_{LIMIT} is selected. This is connected to the CE0 pin on the AD5940.

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

Isolation Capacitors

To conform to IEC-60601 standards 10µA max DC current is allowed to enter the human body. In this application this is guaranteed to be zero due to the addition of isolation capacitors. A value of 0.47μA is selected as they are sufficiently large in capacitance while are also available in small packages making them suitable for wearable electronics. Note C_{ISO1}, the isolation capacitor on CE0 is modified to 15nF so it is suitable for EDA and BIA measurements. See EDA section for details on calculation.

HSTIA Gain Resistor

To calculate R_{TIA}, the gain resistor for the HSTIA, first calculate the minimum impedance/maximum current seen by the HSTIA:

$$Z_{MIN=} \sqrt{(Real)^2 + (Sumof Imaginary)^2}$$

$$= \sqrt{\begin{gathered}(R_{LIMIT} + R_{ACCESS1_{MIN}} + Z_{UNKNOWN_{MIN}} + R_{ACCESS2_{MIN}})^2 \\ +(XC_{ISO1_{MIN}} + XC_{ISO2_{MIN}})^2\end{gathered}}$$

($R_{ACCESS1}$ and $R_{ACCESS2}$ represent resistances in leads connecting the sensor. For calculating Z_{MIN} they are assumed 0 Ω)

Assume Z_{UKNOWN} = 200 Ω.

$XC_{ISO1} = XC_{ISO2}$ = 67.73 Ω @ 50 kHz.

Solving the equation gives Z_{MIN} = 1.2 kΩ.

Note the following:

Maximum voltage is 600 mVpeak.
Max current into TIA = 600mV/Z_{MIN} = 500 μA.
Peak voltage at output of TIA = 900 mVpeak so it is within the ADC range.
Thus, R_{TIA} = 900 mVpeak/500 μA peak = 1.8 k Ω. There is no 1.8 k Ω. R_{TIA} option on the AD5940, so the 1 k Ω option is selected

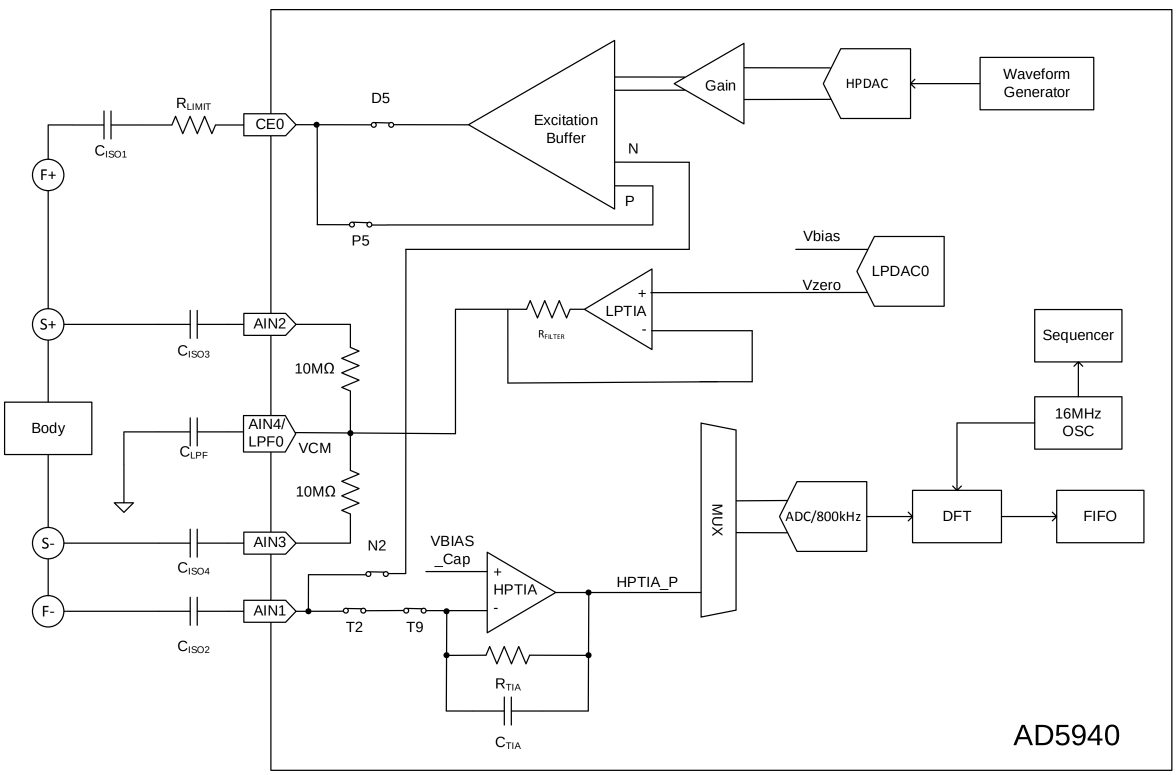

Figure 15. Bioimpedance Signal Path

CALCULATING UNKNOWN Z

The AD5940 uses the sequencer to store commands. A host microcontroller writes the required commands into command memory, and the AD5940 executes the commands automatically. The sequencer runs the commands and fills the data FIFO with the DFT real and imaginary results for both the voltage and current measurements (four data points in total). The host microcontroller reads the data FIFO and uses the real and imaginary DFT results to calculate unknown Z. Calculate the impedance of the sensor using the following equations:

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

$$Voltage\ Measurement\ Phase = tan^{-1} i/r$$

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

$$Current\ Measurement\ Phase = tan^{-1} i/r$$

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

To calculate the impedance Z, use Ohm's law by dividing the voltage magnitude by the current magnitude. Convert the current measurement value into a voltage using R_{TIA}. This gain needs to be taken into account. Therefore, the equation to determine the unknown impedance is:

$$|Z| = \frac{Voltage\ Magnitude}{Current\ Magnitude} \times R_{TIA}$$

TAKING BIA MEASUREMENTS

Hardware Setup

The EVAL-ADICUP3029, EVAL-AD5940ARDZ and AD5940 bioelectric evaluation board and the AD5940 Z Test boards are required to perform BIA measurements. Stack the boards as per Figure 16.

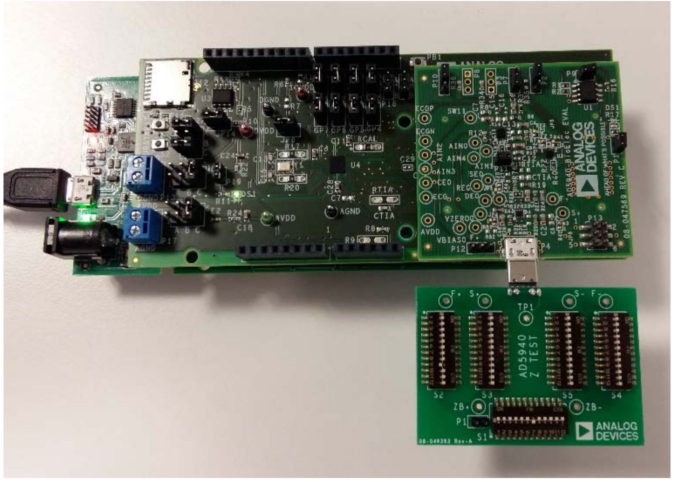

Figure 16: Hardware with Impedance test board

The jumpers on the AD5940-BioElect board do not have any impact on BIA measurements so can remain in the default position.

On the AD5940 Z Test board there are 5 banks of switches labelled S1 – S5. Banks S2, S3, S4 and S5 are used to simulate contact and lead impedances. S1 is used to simulate body impedance. To test measurement accuracy set all switches on S2 – S4 to "ON" position. This sets the contact and lead impedance to zero. Open switch 9 on bank S1 to set the unknown impedance value to 2kΩ as shown in Figure 17.

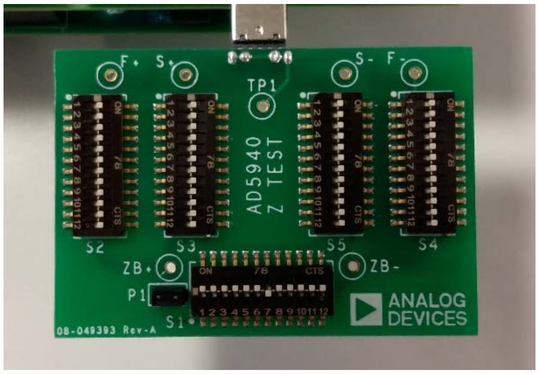

Figure 17: AD5940 Z Test Configuration

Firmware Setup

To use the AD5940 for BIA measurements, use the SensorPal GUI. Refer to the SensorPal GUI section for setup instructions.

Alternatively, there is sample firmware that takes BIA measurements. To run the firmware, IAR Systems Version 8.2.0 or later is required. Refer to the EVAL-ADICUP3029 for details on installation.

Navigate to the **Examples** folder in the software development kit and open the **AD5940_BIA** folder. Open the **ADICUP3029** folder and then the **ADICUP3029.eww** file to open the project workspace in IAR Embedded Workbench.

Compile and build the project. Start the debugger to begin code execution. Open a terminal program such as RealTerm and configure the baud rate to 230400. Select the COM port that the ADICUP3029 is connected to. The measurement results are streamed over a UART and can be saved to a file for analysis etc.

To modify the default application parameters, use the **AD5940BIAStructInit(void)** function. The data structure **AppBIACfg_Type** contains the configurable parameters. For more details on the firmware, refer to AD5940_Library_and_examples.chm file. This is located in the doc folder in the software development kit.

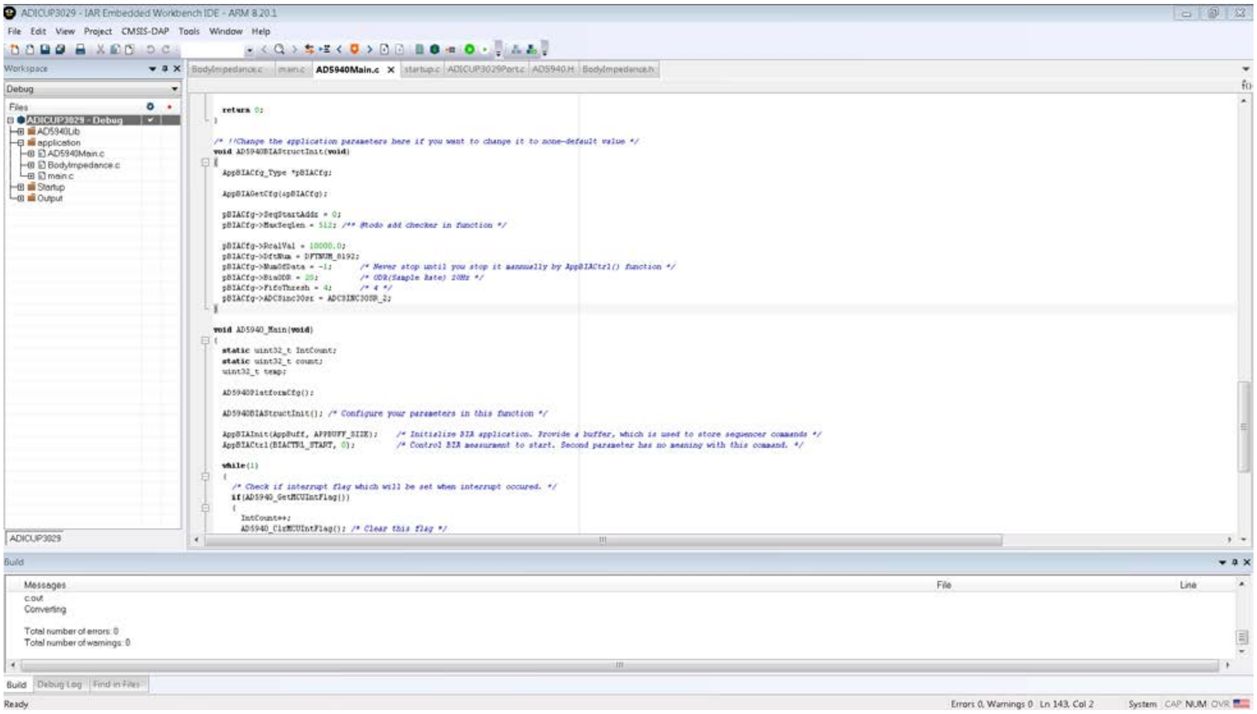

Figure 18. BIA Project in IAR

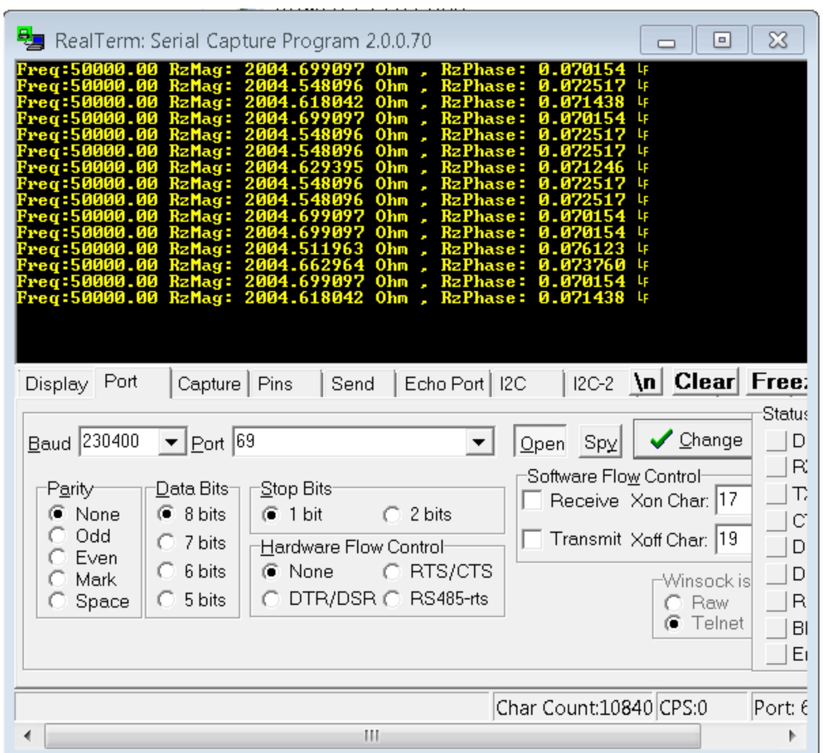

Figure 19. Results Displayed in Terminal

EDA

EDA MEASUREMENT THEORY

EDA is a voltammetry measurement. To measure an unknown impedance, an AC excitation signal is applied across the unknown impedance. The voltage across the unknown impedance is measured. Then the current flow through the unknown impedance is measured. The current is converted to a voltage to be measured by the ADC via the trans-impedance amplifier. A DFT is performed on the ADC data for the current and voltage values. Using the real and imaginary parts, the magnitude is calculated to give $V_{Zunknown}$ and $I_{Zunknown}$.

Use the following equation to calculate the unknown impedance magnitude of the sensor:

$$|Z_{UNKNOWN}| = \frac{|V_{Z_{UNKNOWN}} MAG|}{|I_{Z_{UNKNOWN}} MAG|} \times R_{TIA}$$

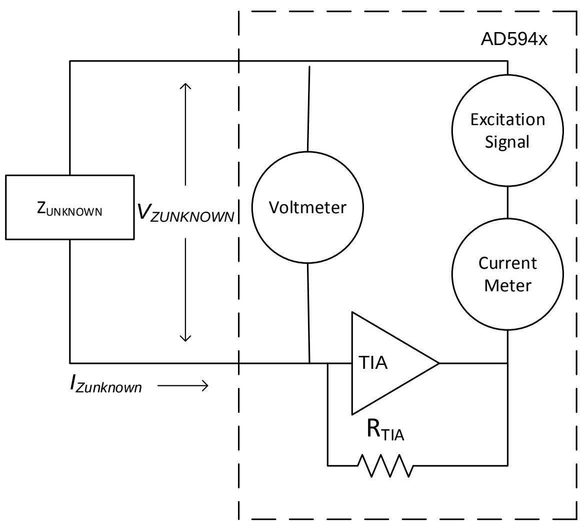

Figure 20. EDA Measurement Diagram

EDA SOLUTION USING THE AD5940

The following section describes the blocks of the AD5940 used to perform EDA impedance measurements. As outlined in the EDA Measurement Theory section, an EDA measurement requires an excitation voltage, a measurement of $V_{Z_{UNKNOWN}}$, and a measurement of the $Z_{UNKNOWN}$ current.

Excitation Signal

The AD5940 uses its waveform generator and low power DAC to generate a low frequency sine wave (≈100 Hz). The sine wave is applied to the sensor via the potentiostat amplifier (PA) connected to the CE0 pin (as shown in Figure 22).

Measuring Voltage

Connect the unknown impedance between the CE0 pin and the SE0 pin. Connect SE0 to the inverting input of the low power TIA. Connect a high precision reference to the TIA to maintain a common mode. To measure the voltage across $Z_{UNKNOWN}$, measure the voltage on CE0, and select VCE0 as the input to the ADC. The measurement sequence is initiated, and a DFT is performed on the measured data. Real and imaginary parts are stored in the data FIFO and are read by the host controller.

Measuring $Z_{UNKNOWN}$ Current

To measure the $Z_{UNKNOWN}$ current, use the same setup used to measure voltage. However, in this case, the current is measured through the TIA. Select the low pass filter output (LPTIA_LPF0) as the input to the ADC. Run the measurement sequence again, and a DFT is performed on the ADC data. The real and imaginary parts are stored in the data FIFO and are read by the host controller.

Calculating Z_{UKNOWN}

The AD5940 uses the sequencer to store commands. A host microcontroller (in this case, the ADICUP3029) writes the required commands to the sequencer. These commands set up the DAC, ADC, and TIA for measurements. The sequencer executes the commands automatically, independent of the microcontroller. The voltage measurement is performed first. An interrupt is generated when the data FIFO is full. The microcontroller then reads the FIFO and stores the real and imaginary DFT results. The ADC mux is then configured to connect the LPTIA low pass filter output to the ADC to measure current. The sequence is run again, and the AD5940 generates an interrupt when the data FIFO is full, which alerts the host controller to read the data.

Use the following equations to determine $Z_{UNKNOWN}$:

$$|V_{MAG}| = \sqrt{r^2 + i^2}$$

$$|I_{Z_{UNKNOWN}} MAG| = \sqrt{r^2 + i^2}$$

$$|Z_{UNKNWON}| = \frac{|V_{MAG}|}{|I_{Z_{UNKNOWN}\,MAG}|} \times R_{TIA}$$

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

CALCULATING DISCRETE COMPONENTS

There are a number of discrete components needed in the system to guarantee safety and accuracy. The following section describes the calculations used to select a suitable:

- Current Limit Resistor
- Isolation Capacitors

Calculating Limit Resistor

1kΩ R_{LIMIT} is used for BIA measurement. Since both measurements share the same electrode, R_{LIMIT} for EDA is 1kΩ also.

Isolation Capacitors

C_{ISO2}, the capacitor on the return path for EDA is selected to be 0.47µA. This is to match BIA measurement. A suitable C_{ISO1} needs to be selected to ensure AC current in the body does not exceed 10µArms in the worst case.

Refer to Figure 21: for worst case condition conditions assume ResistorBody = 0Ω and CapacitorBody is a short circuit. Under this condition largest current will flow in the circuit. Therefore:

$$I_{AC_{RMS_{LIMIT}}} > \frac{V_{EXC_{RMS}}}{\sqrt{R_{LIMIT}^2 + \left(\frac{1}{2\cdot\pi\cdot F_{exc}\cdot Ciso1} + \frac{1}{2\cdot\pi\cdot F_{exc}\cdot Ciso2}\right)^2}}$$

$$V_{EXC_{RMS}} = 1.1V_{PEAK}/\sqrt{2}$$

= 0.777

F_{EXC} = 100Hz

Manipulating the above equation, gives the following to calculate maximum value for C_{ISO1}:

$$Ciso1 < \frac{1}{2\cdot\pi\cdot F_{exc}\cdot\left(\sqrt{\left(\frac{V_{EXC_{RMS}}}{I_{AC_{RMS_{LIMIT}}}}\right)^2 - R_{LIMIT}^2} - \frac{1}{2\cdot\pi\cdot F_{exc}\cdot Ciso2}\right)}$$

Also to be considered is the worst case tolerances for the resistors and capacitors:

- 1% for R_{LIMIT}
- 5% for C_{ISO2}
- 20% for C_{ISO1}
- 10% for F_{EXC}

Thus the equation becomes the following:

$$Ciso1 < \frac{1}{1.2\cdot 2\cdot\pi\cdot 120\cdot\left(\sqrt{\left(\frac{1.1/\sqrt{2}}{10\cdot 10^{-6}}\right)^2 - (1000\cdot 0.99)^2} - \frac{1}{2\cdot\pi\cdot 120\cdot(470\cdot}\right.}$$

C_{ISO1} <14 nF

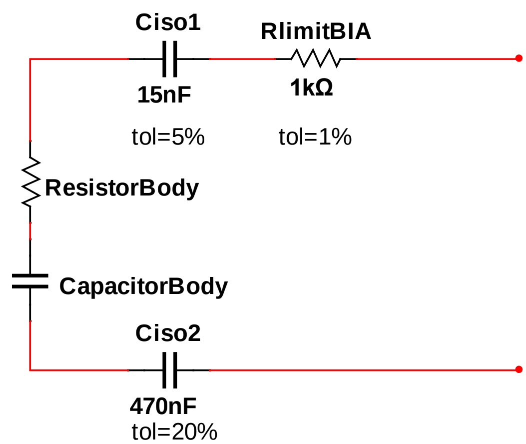

Figure 21: EDA equivalent circuit

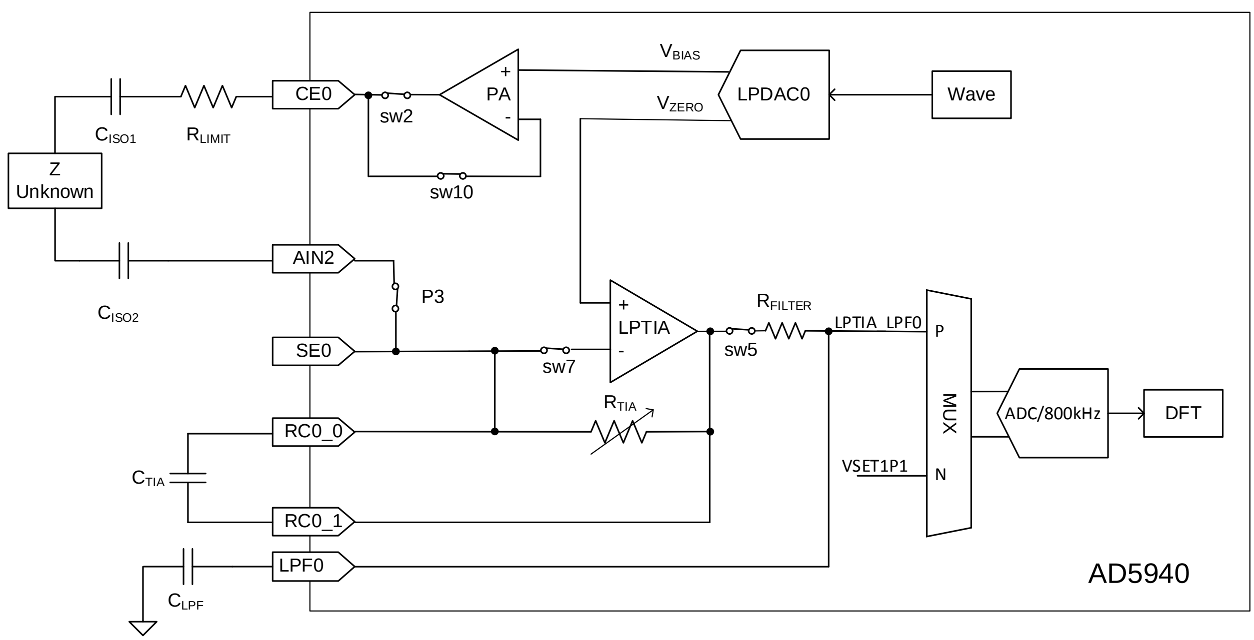

Figure 22. EDA Signal Path

TAKING EDA MEASUREMENTS

Hardware Setup

The EVAL-ADICUP3029, EVAL-AD5940ARDZ, AD5940-BioElec and AD5940 Z Test boards are required to perform EDA measurements.

The default jumper settings on the AD5940-BioElect have no bearing on EDA measurement thus can be left as is.

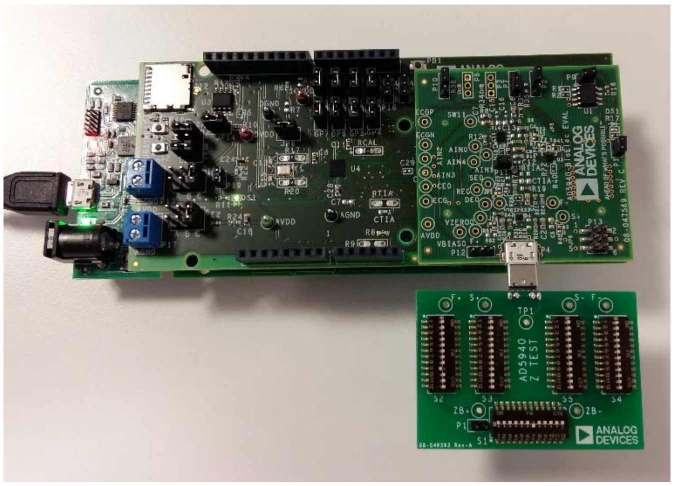

Figure 23: EDA Setup with AD5940 Z Test board

On the AD5940 Z Test board switch banks S2 and S3 are used for EDA measurements. Remove P1 jumper. Close S9.

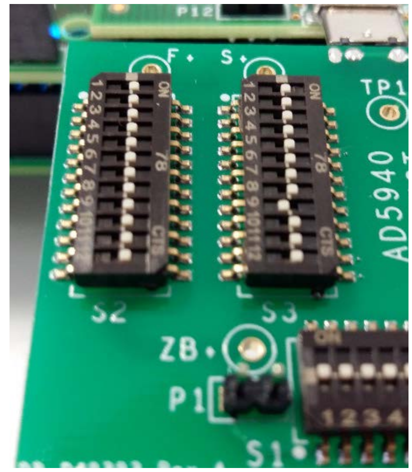

Figure 24: AD5940 Z Test for EDA

Firmware Setup

To use the AD5940 for EDA measurements, use the SensorPal GUI. Refer to the SensorPal GUI section for setup instructions.

Alternatively, there is sample firmware that takes EDA measurements. To run the firmware, IAR Systems Version 8.2.0 or later is required. Refer to the EVAL-ADICUP3029 for details on installation.

Navigate to the **Examples** folder in the software development kit and open the **AD5940_EDA** folder. Open the **ADICUP3029** folder and then the **ADICUP3029.eww** file to open project workspace in IAR Workbench.

Compile and build the project. Start the debugger to begin code execution. Open a terminal program such as RealTerm and configure the baud rate to 230400. Select the COM port that the ADICUP3029 is connected to. The measurement results are streamed over a UART and can be saved to a file for analysis etc.

To modify default application parameters use the **AD5940EDAStructInit(void)** function. The data structure **AppEDACfg_Type** contains the configurable parameters. For more details on the firmware, refer to the **doc** folder located in the software development kit.

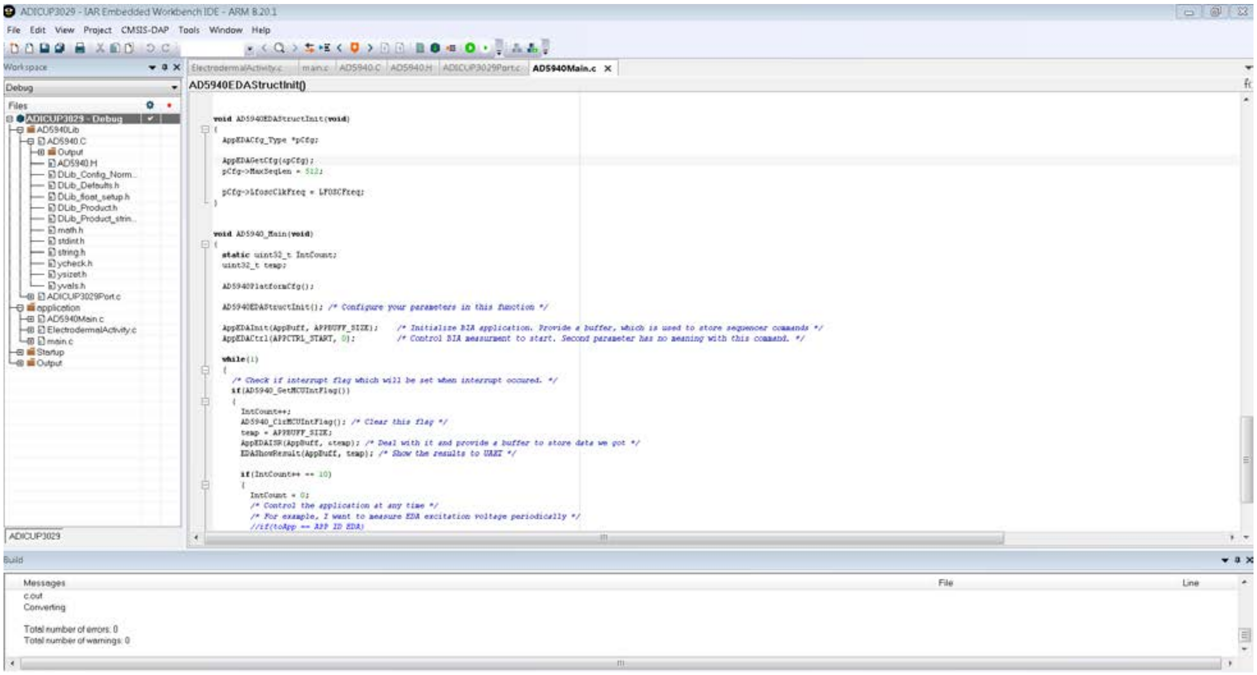

Figure 25. EDA Configurable Parameters in IAR

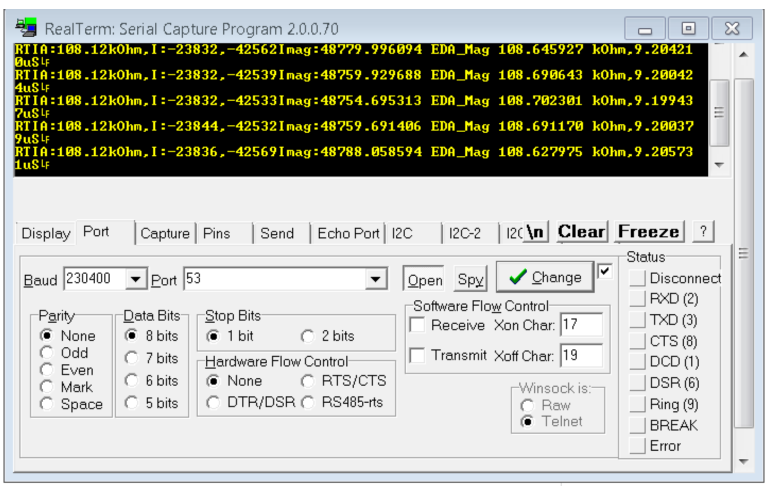

Figure 26. EDA Measurement Results

SENSORPAL GUI

The AD5940 bioelectric evaluation kit has a desktop GUI. This GUI is designed to provide an interface to quickly configure measurements and display measured results.

INSTALLING SENSORPAL

To install the SensorPal GUI, take the following steps:

1. Run the **SensorPal.exe** installer.
2. Connect the ADICUP3029 and the AD5940 to the PC and navigate to *C:\Analog Devices\SensorPal\Firmware Files* (the default install path for the GUI)
3. Drag and drop the **SensorPal-Firmware.hex** file onto the **DAPLINK (D:)** drive, which installs the required firmware on the ADICUP3029 so the board will work with the GUI.
4. Power cycle the ADICUP3029 board.
5. Open the SensorPal GUI and connect to the COM port that the ADICUP3029 is connected to.

TAKING MEASUREMENTS USING SENSORPAL

Figure 27 shows the SensorPal main screen. On the left hand side of the main screen is the **Tool Belt**. Under **Bio-Electric Techniques**, there are three options: **Body Impedance**, **Electrodermal Activity**, and **Electrocardiogram**.

To run one of these measurements, drag and drop the measurement into the **WORK AREA**. Only one measurement technique can be in the **WORK AREA** at a time. To get information about a measurement technique, enable **Help Mode**. A number of configurable parameters appear under the **Selected tool:** heading. Modify these configurable parameters as required and click **Measure**. The results are displayed in the graph area but can also be saved to an Excel® file.

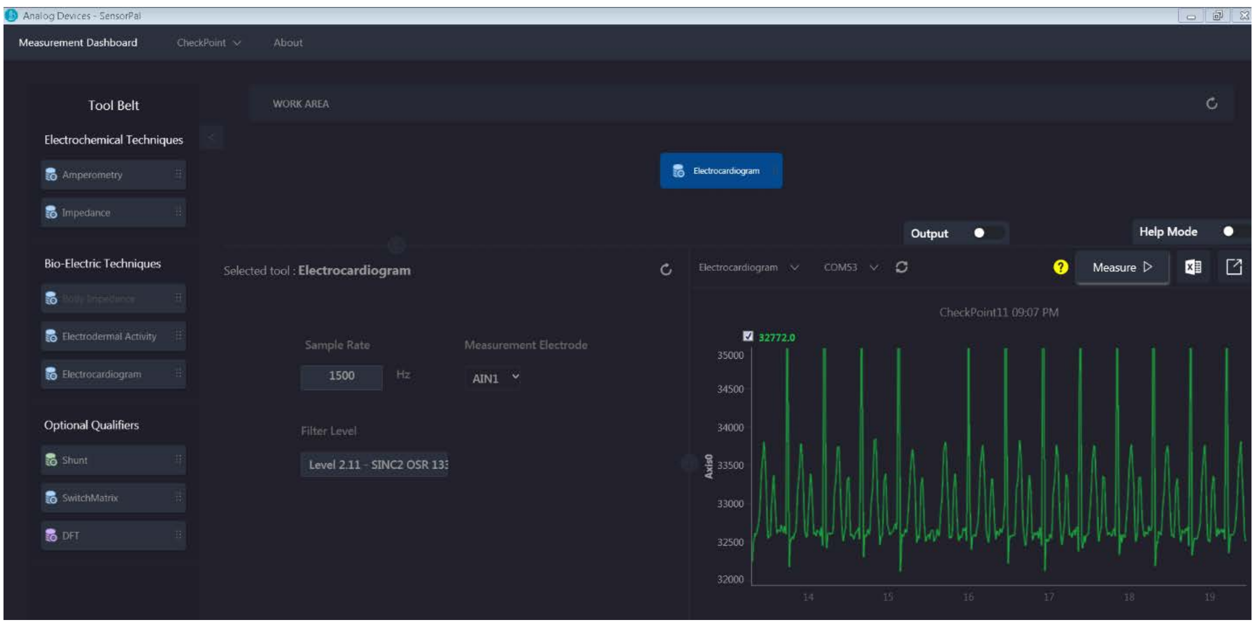

Figure 27. SensorPal GUI Main Screen

LIMITATIONS ON USE AND LIABILITY

The application described in this application note is specific to the AD5940 and the AD8233 for use with the EVAL-ADICUP3029 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.

©2018 Analog Devices, Inc. All rights reserved. Trademarks and registered trademarks are the property of their respective owners.
AN16807-0-5/18(0)